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THE UNIVERSITY OF ALBERTA

Travel Behaviour and Equilibrium in Networks of Signalized Intersections

by

© Brice William Stephenson

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF Master of Science

IN

Civil Engineering

Department of Civil Engineering

EDMONTON, ALBERTA

Fall 1981

To Lorna

Abstract

Transportation Systems Management has developed from the recognized need to examine both supply and demand, when evaluating transportation problems. Considerable research is now underway to develop techniques that may be used to assess the impact of a wide variety of Transportation Systems Management proposals.

In Edmonton, the planning and implementation of a number of traffic management plans identified a need to understand the relationship between travel behaviour and the state of the transportation network. In 1979, three sections of the Edmonton road network were evaluated to determine the effects of traffic management schemes on travel equilibrium.

Traffic equilibrium has generally been accepted as equalling a stability in travel times and route selection within a network. The traditional traffic assignment models have generally dealt with only the relationship between travel times and route selection. In this treatment, a change in the capacity of some portion of the network affects travel time, thereby altering route selection. A new 'equilibrium' system is eventually established, as given by new network travel times and route selection.

The results of the Edmonton surveys indicated that travel behaviour is influenced not only by travel time, but also by queueing. Significant changes in either queueing or delays, resulting from a capacity change, appear to affect not only route selection, but also the time selected to begin the journey. Substantial route re-assignment was observed, in Edmonton, when travel times changes by 4 minutes or more, or when queue lengths changed by 40 vehicles or more. Temporal re-assignment was noted only after route re-assignment failed to eliminate an additional 5 minutes of travel time. Mode selection may also be influenced by network changes, but the data collected in this study did not confirm this hypothesis.

A number of researchers have developed a new generation of traffic models to be used for the assessment of Transportation Systems Management strategies. One such model, CONTRAM, was applied to one of the Edmonton

study locations. Results achieved with CONTRAM agree well with measured results, except in the area of temporal assignment.

In the final chapter, a suggested methodology for assessing Transportation Systems Management alternatives is presented. The proposed methodology combines the use of CONTRAM with measured results in Edmonton.

Acknowlegements

The author would like to express his gratitude for the assistance provided throughout this study by numerous individuals from the University of Alberta, Civil Engineering, the City of Edmonton; Engineering Department and Transportation Systems Design Department, and the G.C.G. Engineering Partnership.

The guidance and support provided by Professor Stan Teply throughout the development of this project is gratefully acknowledged. Without his direction and suggestions, the objectives of the research could not have been met.

The assistance of John Schnablegger, now with the G.C.G. Engineering Partnership, was instrumental in providing the resources necessary for the data collection and analysis. His many suggestions and guidance in the study have been appreciated.

The manpower to conduct the data in this study, and a large proportion of the data analysis were provided by the City of Edmonton. Without this assistance, it would not have been possible to meet the objectives of the study.

The British Transport and Road Research Laboratory have assisted this research considerably through the provision of the CONTRAM program.

I would like to thank Doug Hunt, for the preparation of the computer programs for data analysis, and Kevin Warner, for his work in preparing the figures.

Finally, I would like to thank my wife, Lorna, for her patience and encouragement in the completion of this work.

Table of Contents

List of Tables

List of Figures

Figure		Page

Figure		Page

I. INTRODUCTION

A. The Peaking Problem

In urban centers, trips for many purposes are made by individuals during each day. Of these, trips between the home and workplace form a major component. This fact, combined with near-standardized working hours results in a peaking of transportation demand at certain times of the day; notably in the morning and afternoon peak hours. Recognizing that peaks in demand exist, the Transportation Engineer is faced with the task of designing for peak demand by balancing the costs of congestion against the cost of additional transportation facilities.

The current high construction costs and long lead times for new construction have led to a greater emphasis towards maximizing the use of existing transportation facilities. Plans for new construction are increasingly scrutinized to ensure that the best use of scarce capital is being made. This has led to an increased concern for 'management' of transportation systems.

B. The Transportation Management Concept

Transportation Management attempts to balance the transportation supply and demand equation to ensure that an optimal use of the transportation system is achieved. This 'optimum' would result from a minimization of some combination of economic and environmental impacts, and maximization of transport services.

In the broad sense, Transportation System Management (T.S.M.) co-ordinates the efforts of all agencies involved in the planning, design and operation of transportation facilities. As a result, all modes of travel, and time frames from immediate to long range must be considered.

Examples of the type of measures evaluated in a T.S.M. program might include:

a. evaluation of a detour plan

b. impact of a residential traffic control plan

c. implementation of a one way street system

d. impact of flexible working hours

e. prediction of the effects of a bus only lane

f. changes in land use (ie, development of a regional shopping center)

g. comparison of freeway and arterial options in a corridor

To evaluate alternative transportation management strategies, an understanding of underlying travel behaviour and trip making characteristics is essential. Most existing models for the assessment of transportation options restrict themselves to the application of standard transportation planning or operations techniques.

In Edmonton, since 1974, a great effort has been put forth to ensure that the best use of existing transportation facilities is being made. A variety of transportation management measures have been proposed or implemented. The evaluation of proposed measures has led to the conclusion that additional techniques beyond conventional planning or operations methods are required.

Two transportation management plans in Edmonton that were subjected to detailed analysis are presented here. These included a review of capacity requirements in a portion of the downtown network, and an improvement plan covering a large portion of south-central Edmonton.

a A Study of Traffic in the Eastern Portion of the Downtown

In 1977, the eastern portion of Edmonton's downtown core was studied as part of an M.Eng. project at the University of Alberta (Ref. 9), including the network area shown in Fig 1.1.

The objective of this study was to determine the gate intersections, where flow breakdown would occur, and to identify required transportation management measures in the area.

The study dealt with the development of optimized signal timings for the following alternatives:

a. 1976 volumes

b. 1981 traffic assignment model predictions

c. assuming a 25% increase in volumes

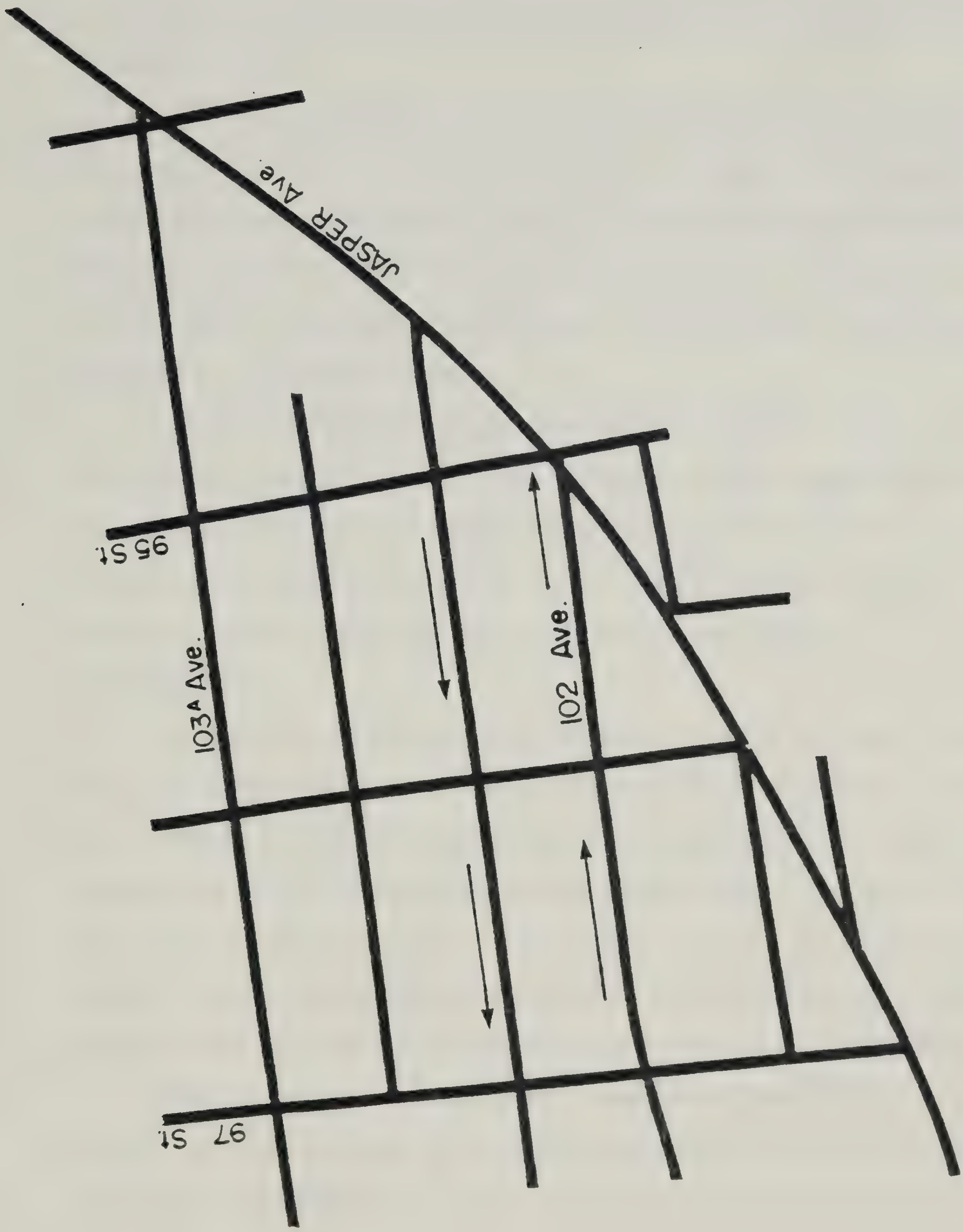


Figure I.1 The Eastern CBD in Edmonton

In each case, a network operations model, TRANSYT version 5, was used to design signal timings and evaluate the network's performance. Using either the 1981 projections, or the 25% volume increase, some intersections were brought to capacity. As a result, excessive delays were predicted to occur for some movements.

Due to the availability of 3 parallel north-south and east-west routes in the area, it was not considered reasonable to expect one route to operate with excessive delays while parallel routes of the same length experienced minimal delays. As a result, traffic flows in the network were manually re-assigned, and timings were re-optimized. This process was re-iterated until delays had been equalized on all parallel routes.

While the TRANSYT model permits both simulation and signal optimization in a network, the model could not re-assign traffic demand and volumes. The assumption that delays on parallel routes would be the same is not necessarily correct. An accurate prediction of flows would require the use of an origin - destination table, which was not available for this study.

b Project Uni

By the mid 1970's, severe congestion existed on major arterial roadways near the southern approaches to Edmonton's downtown, and in the vicinity of the University of Alberta. Transportation planning studies had identified that major expenditures would be required to accomodate future growth in traffic volumes. The long lead times for new facilities, and the level of congestion led to demands for immediate solutions to the traffic problems. As a result, it was recommended that traffic operational improvements be implemented in the area.

The Project UNI transportation management plan (Figure 1.2) evolved from a major operational study to reorganize and optimize traffic flows in south-central Edmonton. The majority of this plan was implemented in the fall of 1980, following a two year study period. The plan featured the adoption of numerous one way streets, including two bridges. A number of minor geometric improvements and traffic management schemes were also implemented as part of Project UNI.

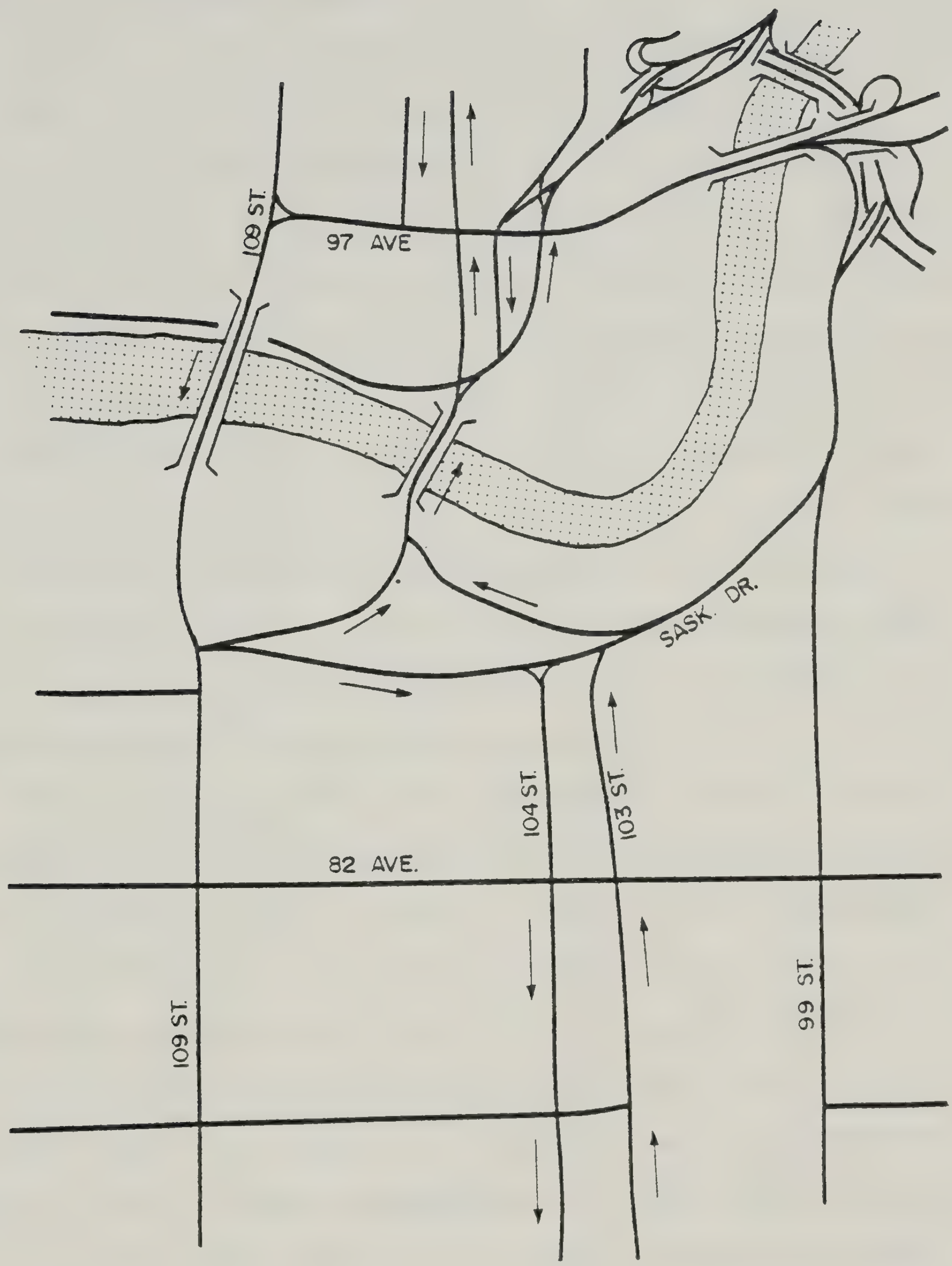


Figure 1.2 Project UNI

The network area involved, and the large number of changes introduced, forced drivers to re-consider their route selection. In particular, the introduction of one way streets forced a major revision of flow patterns. A prediction of traffic flows in the area was necessary in the design of signal timings, and for the evaluation of the project's benefits.

To evaluate Project Uni, both the City of Edmonton's computerized traffic assignment model and a manual assignment were used (Ref. 16,17).

The computerized traffic assignment led to the conclusion that little change would occur in the travel times on the network. At the same time, very little change in demand was predicted, aside from changes in the immediate vicinity of the one way street system. This result was not surprising, in that traditional network assignment models are not sensitive to changes in intersection controls or signal timings. Control measures such as turn restrictions or left turn phases could not be simulated at all, due to the resulting increase in network complexity. These same intersection control changes, however, are used in traffic operations as accepted techniques for reducing delays and improving traffic flows. Intuition suggested that flow changes could also be expected, and that the new system would improve overall network performance.

The manual assignment assumed that existing flow patterns would be maintained except at congested intersections. At these bottlenecks (in the bridge area), it was assumed that volume / capacity ratios, and therefore delays, would be balanced on parallel routes (near 95% of capacity). As with the case of the Eastern CBD analysis, this assumption could not be supported, as little information about origins and destinations of traffic flows in the area had been obtained. In fact, flows on the study area boundaries were assumed to be the same, 'before' and 'after' project implementation. The manual assignment was used to perform intersection delay analysis. The summation of intersection delays throughout the area indicated that a major improvement in system performance would occur with the introduction of Project UNI.

Since the implementation of Project UNI in the fall of 1980, 'after' studies have been performed to evaluate the effectiveness of the scheme. Figure

1.3 indicates projected volumes from both assignments, compared to actual volumes, measured between fall, 1980 and spring, 1981 for the morning peak hour. An examination of Figure 1.3 indicates that neither the operations or planning approaches were correct in their assessment of predicted traffic flows. The manual assignment did come closer to matching actual volumes, but significant differences do exist on some links (99 Street and Saskatchewan Drive). These differences resulted in a number of negative secondary impacts that had not been anticipated in the planning stages.

Project UNI clearly indicated that a different approach to T.S.M. evaluation was required to ensure that all major impacts of proposed changes were known in advance.

c The Problem

Additional examples of transportation management measures could be drawn from Edmonton and other urban centers both inside and outside North America. The examples discussed in the previous section were confined only to route assignment. Changes in mode selection and peaking behaviour are other factors requiring assessment for a thorough evaluation of T.S.M. proposals.

It appears, then, that existing transportation planning or traffic operations techniques are not by themselves sufficient to deal with many projects in the category of Transportation Management. Apparently, a review of the underlying principles of trip making behaviour is required, in order that a new evaluation technique can be developed.

The transportation equilibrium concept is felt to be important in any evaluation of travel behaviour. Evaluation of the response of individuals to a change in the transportation system should provide the necessary tools for examining transportation management proposals.

C. The Equilibrium Concept

Classical Economics often studies the relationship between the cost of a product and the quantity consumed. This relationship between cost and production is often shown through the use of supply and demand curves, such as that

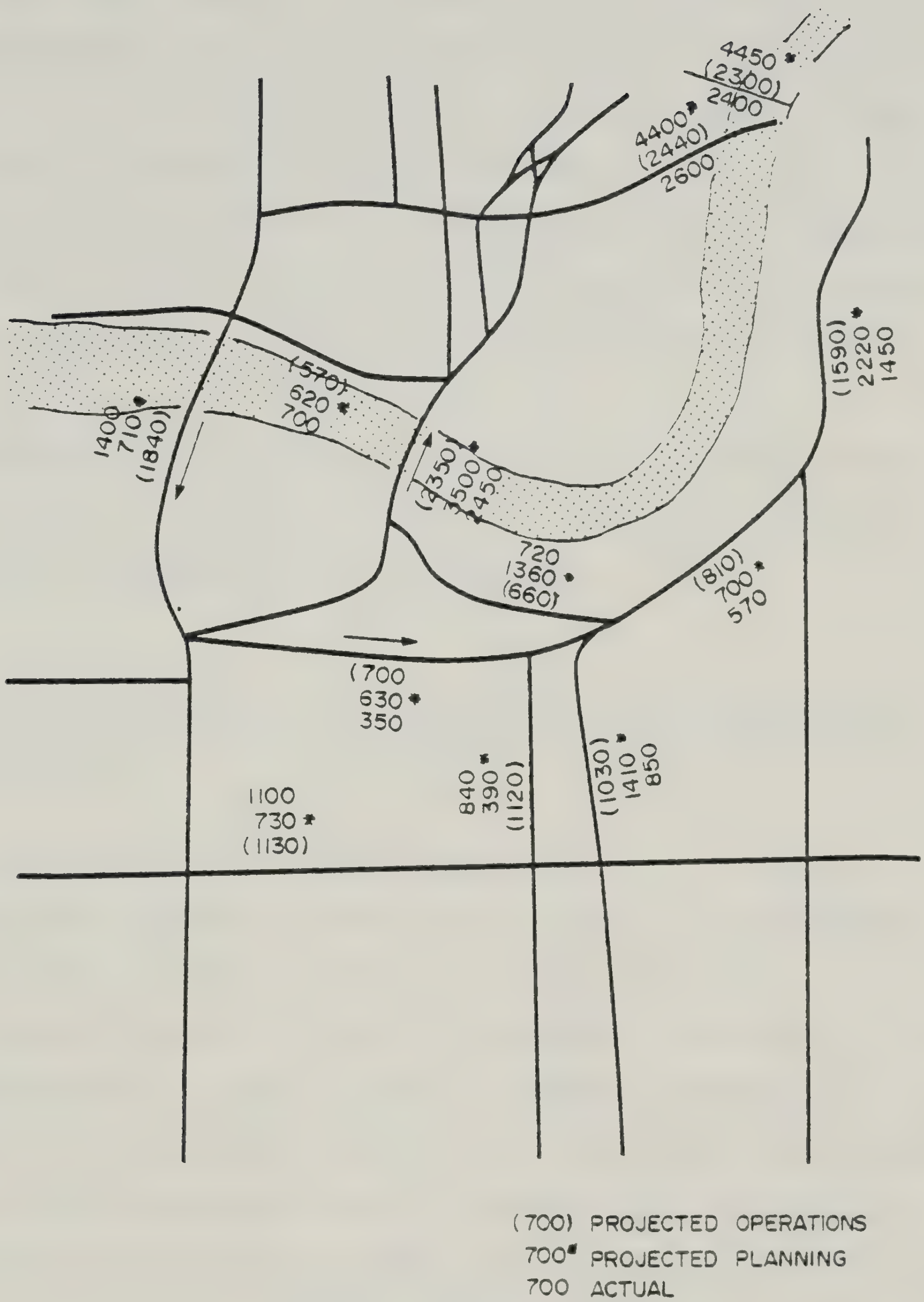


Figure I.3 Project UNI Projected versus Actual Volumes

depicted in Figure 1.4. The intersection of these two curves indicates an equilibrium point, where the quantity supplied equals the quantity consumed. Any shift in the supply curve results in a movement along the demand curve, and the eventual establishment of a new equilibrium point. This new equilibrium is defined by a new cost and level of production for the commodity.

Travel behaviour may be analyzed using an analogy to the Economics models. In a transportation system, supply is equivalent to capacity available, and demand is total travel demand. A particular equilibrium point would be defined by a unique 'cost' of trip making and the observed number of trips being made. An alteration in network capacity results in movement along the travel demand curve to a new equilibrium point. The new equilibrium point is established with a different 'cost' of travel and volume of trips.

The application of the equilibrium concept in transportation was first outlined by Wardrop in 1952 (Ref. 41). Wardrop stated that an equilibrium state in transportation is characterized by two principles:

> "1) The journey times on all the routes actually used are equal and less than those which would be experienced by a single vehicle on any unused route.
>
> 2) The average journey time is a minimum."

Wardrop also identified that these two principles will not necessarily lead to the same result. An example will serve to illustrate this point.

For movement between an origin and destination, two routes are available; routes A and B. Route A is short in time, but relatively congested, while route B takes longer, but is uncongested. Using the first equilibrium principle, drivers would behave selfishly, selecting route A to minimize their own travel time, but imposing additional travel time on all other users. With the second principle, the driver would select route B to minimize average journey time in the system, without regard to his own additional travel time. It can be shown that the first equilibrium principle is similar to the average cost pricing principle of micro-economics, while the second principle more closely resembles the marginal

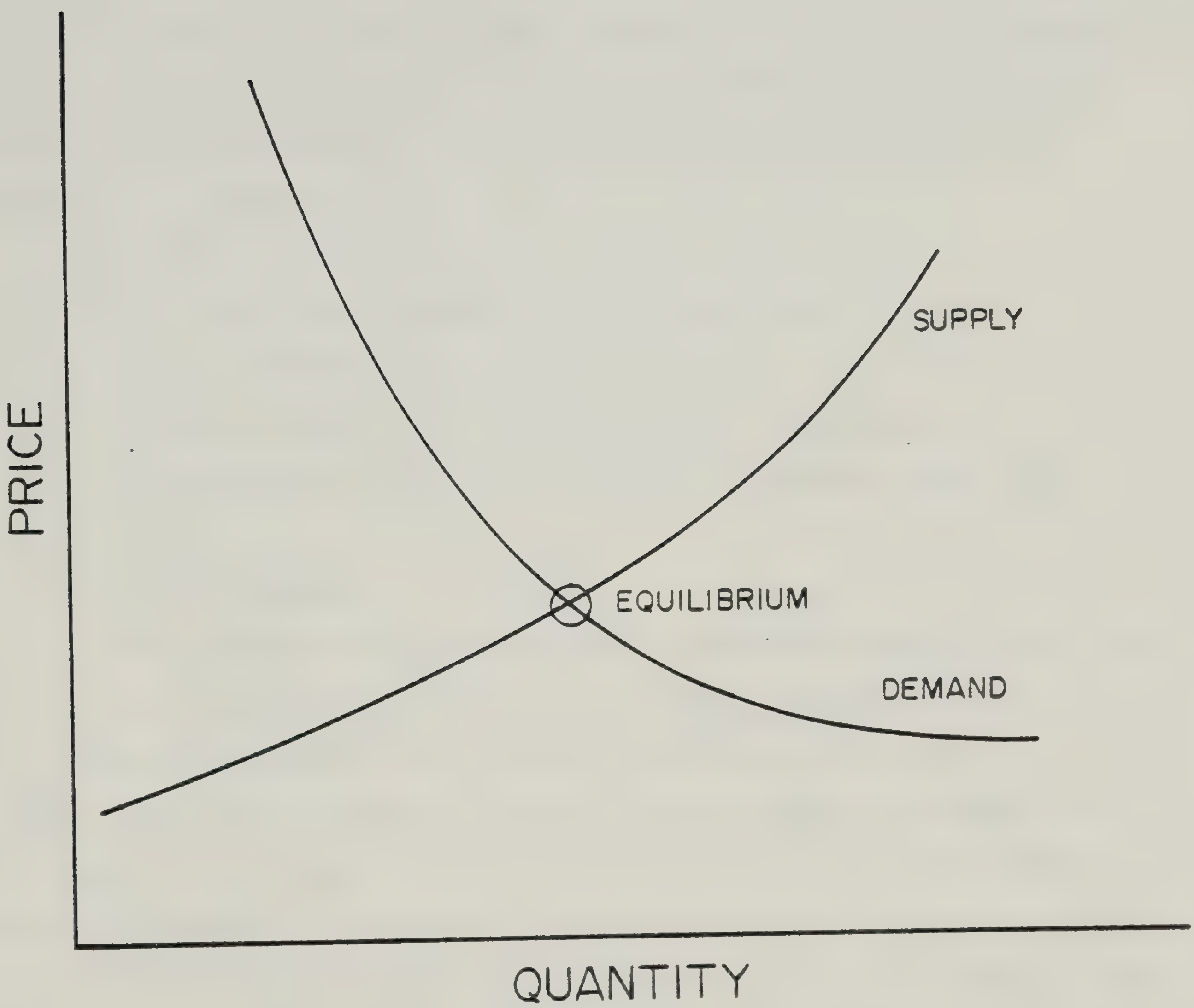


Figure 1.4 Supply and Demand

cost pricing principle.

If a change in capacity alters travel time on one route in the network, a change in route selection would be expected. A change in route selection would cause the shifting of trips between routes, until a new equilibrium was established. Many of the traffic assignment models used in transportation planning, make use of this approach.

Considering route selection alone may not provide a sufficient explanation of travel behaviour. As a result, several researchers have put forth a broader view of equilibrium that considers transportation changes that may occur at a number of levels. Movement to a new equilibrium point may consist of a combination of these factors:

a. route re-evaluation:

   The driver selects route of minimal travel cost.

b. time of departure re-evaluation:

   Time of departure is altered so that cost is minimized. The inconvenience of early or late departure is balanced against travel cost.

c. mode selection:

   The selected mode is re-evaluated to determine whether relative costs have changed enough to warrant a change in mode.

Other travel decision levels beyond these three might include, for example, not making the trip, or relocating the trip origin or destination. The time required to re-establish equilibrium would be longer with each succeeding level in the hierarchy of choices.

Up to this point, discussion has indicated that the 'cost of travel' is the key influence on travel behaviour. This 'cost of travel' has generally been equated with travel time in most transportation planning models. A more detailed investigation is not often conducted, probably due to a lack of available resources. It is suspected, however, that if a detailed examination of equilibrium were considered, the 'travel cost' might be found to include factors in addition to travel time. Travel cost might consist of:

a. – free flow travel time

b. – delay

c. – queue length

d. – number of stops

e. – comfort, security

f. – direct monetary cost (ie fares)

g. – other factors

D. The Purpose of this Research

The discussion of previous sections has indicated a need for models capable of evaluating alternative transportation management strategies. Existing planning and operational techniques do not seem to provide sufficient information for decision making or comparisons. Research is required to develop more appropriate techniques, based on detailed traffic studies and an examination of traffic equilibrium.

a Scope of this Research

The problem at hand would require enormous data collection and analysis to gain a full understanding of travel behaviour. The cases discussed here are restricted, due to a lack of resources, to the following situations:

a. urban networks, primarily consisting of signalized intersections and arterial roads

b. span between 'before' and 'after' limited to 3 months, with an upper limit of 6 months

c. network changes restricted to roadway capacity changes only

These limitations resulted in analysis being restricted to transportation choices involving only route assignment, temporal assignment and mode selection. Network characteristics considered to influence equilibrium were restricted to include only intersection delay, queue length, number of stops and general observations.

b Research Objectives

The objectives of the research were also confined due to the limits of manpower and resources available for the studies. The study itself consisted of

four sections:

a. review of existing methodologies for modelling travel behaviour

b. data collection and study of network changes in Edmonton

c. simulation of network using existing 'state of the art' models

d. development of an approach to the assesment of T.S.M. strategies

The primary goal of the research is the development of techniques that enable the evaluation of transportation management strategies. To fulfill this objective, a number of secondary objectives had to be met:

a. Assess what network characteristics influence travel equilibrium (from surveys).

b. Determine the extent of route, temporal and mode re-assignment caused by a change in network characteristics (from surveys).

c. Determine what revisions to existing models are necessary to match observed traffic equilibrium changes in the street.

The transportation model selected for use in this study was CONTRAM (CONtinuous TRaffic Assignment Model), under development by the Transport and Road Research Laboratory in England. It is hoped that the results of analysis using CONTRAM will form a useful input into the continuing development of this program.

II. REVIEW OF EXISTING METHODOLOGIES

Chapter 1 outlined the experience at two locations in Edmonton in the use of planning and operations models in the assessment of T.S.M. type improvements. It was concluded that these techniques do not enable a thorough assessment of the impacts caused by transportation network changes.

In this chapter, existing techniques for network assignment, and operational analysis are initially presented, together with the results of a number of investigations into traffic equilibrium. At the end of the chapter, new models that combine operational and planning techniques are presented. These combined assignment and optimization models represent a promising step in the development of models for the efficient management of transportation networks.

A. Network Assignment Models

The traditional four step transportation planning process is made up of trip generation, trip distribution, mode split and traffic assignment. Through the use of this process, alternative land use and transportation plans can be tested and compared. The 'travel cost' between origins and destinations enters all steps in the process, with the exception of trip generation, but traffic assignment represents the section of most use in the comparison of alternative transportation strategies. The traffic assignment model loads vehicles onto a specified road network. The model itself consists of two major sections:

a. a 'tree-building' algorithm that uses dynamic programming to construct feasible routes between origins and destinations in the network

b. a decision criteria to determine how vehicles should be loaded onto the network between origin-destination pairs

A discussion of 'tree-building' algorithms will not be presented, as the actual algorithm used will have little impact on the program results. A number of efficient algorithms do exist for the determination of feasible network paths.

The decision criteria results from the interpretation of Wardrop's traffic equilibrium concept, stated in Chapter 1. Wardrop indicates that the first equilibrium principle is more likely to be followed in practise (Ref. 41), as

drivers are generally more concerned about their individual welfare than the societal optimum. The results of research by Yagar (Ref. 45) indicates that actual travel behaviour in a network falls between the two principles for a freeway and arterial network in Berkeley, California.

a Model Types

A number of traffic assignment techniques have evolved since Wardrop's discussion of equilibrium in 1952. The most widely used models include:

a. 'all-or-nothing' assignment

   The 'all-or-nothing' assignment routine was the first to be developed. All traffic between an origin-destination pair is loaded onto the shortest time route. A problem with the use of this model is that it may be unstable under certain circumstances. Completely different results may be obtained with only a slight change in comparative link travel times (ie a complete shift of flows from one route to another).

b. capacity restrained assignment

   A capacity restrained assignment initially assigns on an 'all-or-nothing' basis. Link volumes are then adjusted to ensure that flows from heavily loaded links are re-distributed to other routes in the network, according to some decision rule.

c. multipath assignment

   Multipath assignment routines, such as that developed by Dial (Ref. 21), select a number of feasible paths between each origin and destination, before traffic is assigned. The proportion of flow assigned to each alternate path is a function of the route travel time relative to the shortest route.

d. mathematical programming

   Mathematical programming techniques attempt to minimize total travel time in the network subject to the constraint of flow conservation.

The first three techniques assume Wardrop's first principle applies, while mathematical programming is based on application of Wardrop's second principle.

The method selected depends on the nature of the network and the level of congestion that exists on links in the network. For example, an 'all-or-nothing' approach would be suitable it the network was well undersaturated, or had few alternate routes.

As an extension to these methods, 'equilibrium' assignment models have been developed to attempt to directly determine flows using either of Wardrop's principles. This is done by considering link travel cost as increasing functions of link flows, but not having a particular capacity limit. Florian and Nguyen (Ref. 22) compare one of these equilibrium assignment models to measured results using 1970 data for the City of Winnipeg. The assignment results corresponded quite closely to measured volumes. It was determined, however, that the model was quite sensitive to the link speed-flow curve used. It should be noted that the Winnipeg network was under-saturated. Application of this model to saturated networks was not documented. As a result, the sensitivity of the model to network congestion is unknown.

b Travel time relations

Assignment models load vehicles onto routes based on 'travel cost'. This expression for travel cost is then a key influence on the predictions made by each model. It appears that the 'cost of travel' in network assignment models is most often equated to link travel time. The most commonly used travel time relationships are presented in this section. A comparison of various travel time models is presented in order to determine their suitability in a network of signalized intersections.

Branston (Ref. 8) reviews the current 'state of the art' in travel time functions. The methods used may be broken into several groups:

- speed-flow relations (freeway based)
- speed-flow relations for arterials
- explicit treatment of intersection delay

In each case, the travel time expressions must be simplified to match the level of detail used in the network description of traffic assignment models. This

restriction means that most models cannot deal effectively with the simulation of arterial traffic. As a result, most of these travel time models either tend to infinity or reach some upper limit when capacity is reached. Several researchers have provided improved models that enable a better prediction of travel times for operation beyond capacity (see Branston (Ref. 8) and Akcelik (Ref. 2)).

The major problem with travel time simulation remains, however, in the treatment of arterials and intersections. In the context of transportation planning, most models treat intersections as nodes connected by links. Most often, only a single link is used to represent an intersection approach. This does not allow the seperate representation of turning movements, with their lower capacity. Intersection capacity is often expressed as an average link capacity, for each class of road. Travel times calculated on the basis of this link capacity will not generally agree with actual travel times.

Attempts to mix intersection delay with link speed-flow curves results in a relative comparison, but realistic delay and travel times are not predicted. This attempt to use detailed intersection delay is also inconsistent with the level of detail in use in the network. For example, the City of Edmonton uses a combined freeway and arterial speed-flow curve, which includes an expression for intersection delay (Ref. 19). The specific link travel time relationship employed in Edmonton is:

$$T = Tf + Ts$$

$$Tf = 3600*D/SR$$

$$Ts = ((1.0 - (GT/100))^2*CL)$$

where:

$$SR = (1/3* ((4*SL) - SC)) - (4/3 * (SL - SC) * (V/C)^2)$$

when SC > SR, then:

$$SR = 100/(((SL - SC) * V/C) - 5)$$

T - link travel time

Tf – free flow travel time

Ts – signal penalty

D – link length (miles)

SL – legal speed limit (mph)

SC – critical speed = 20 mph

GT – % green time in the signal cycle (CL)

This travel time expression and traffic assignment model were calibrated against 1970 link volumes for Edmonton. At that time, undersaturated conditions existed in almost all portions of the network.

The expression for travel time consists of a free flow portion and a signal delay portion (which is excluded for true free-flow links). The signal delay is comparable to the uniform delay of queueing theory. Link capacity is taken as either the true link capacity (freeways) or the 1965 Highway Capacity manual saturation flow at the stopline of links ending at a signal or priority ruled intersection.

The extent of the discrepancy between the travel time predictions using Edmonton's traffic assignment model and delays based on field measurement at signalized intersections is illustrated in Figure 2.1. Figure 2.1 indicates that little difference exists between the two travel time curves until v/c approaches 100%. Beyond this point, however, the traffic operations model calibrated to actual delays predicts significantly longer travel times than the traffic assignment travel time model. This agrees with the findings of Branston (Ref. 8) that most existing travel time equations ignore or fail to adequately treat the impacts of saturation on link travel times.

In addition to the discrepancy noted here between operations and planning model predictions, other limitations to the application of traffic assignment models exist. At a signal, changes in timings, phasing or turn restrictions can result in substantial capacity and delay changes. The assignment model makes use of either fixed link capacity or fixed signal timings, on the assumption that program input represents an 'optimal' initial condition. Many T.S.M. improvements can simply not be modelled with assignment models. For example:

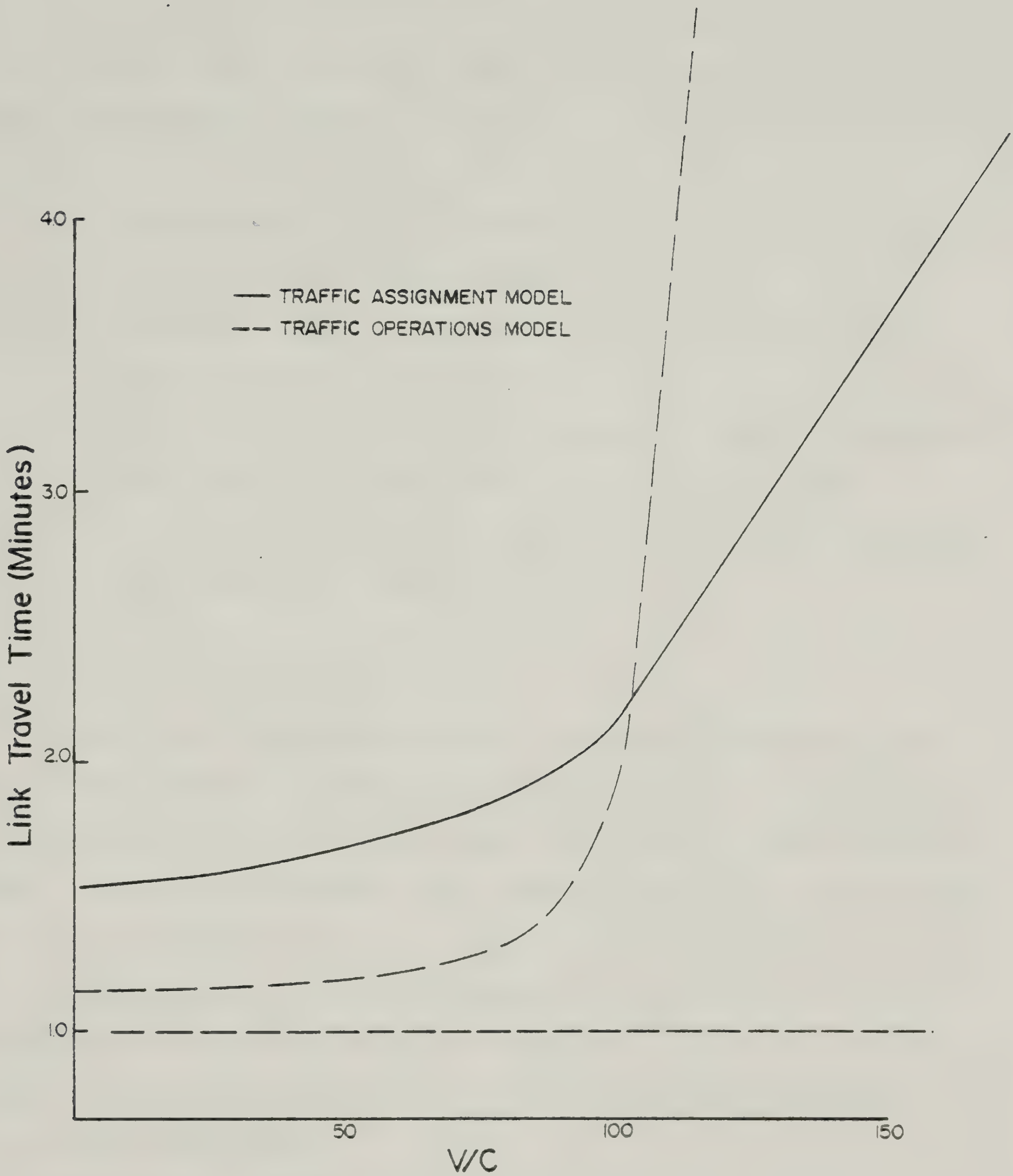


Figure II.1 Travel Time – Traffic Assignment versus Intersection Delay

a. revisions of signal timings or phasing

b. introduction of signal co-ordination

c. neighbourhood traffic control plans

d. change in intersection controls

e. transit priority

In summary, the use of conventional traffic assignment models for evaluating transportation management strategies is not considered adequate for the following reasons:

a. Signal timings are assumed fixed. As a result, signal timings and phasing cannot be altered as volumes change.

b. Intersections are not represented in a form that allows detailed analysis of turning movements.

c. Most travel time expressions are designed for relative comparison, and do not agree with actual travel times in arterial networks.

d. The problem of operation at capacity is not adequately dealt with in existing assignment models.

B. Traffic Operations Simulation

Another major contribution to urban transportation modelling is made through traffic operations techniques. This section presents a description of traffic operations techniques that are applied in Alberta. The models fall into the category of individual intersections, and systems of intersections. As a common feature, each technique assumes that a set of fixed design volumes is known. The discussion here is restricted to signalized intersections only, as these represent the most common form of arterial traffic control. Additional techniques do exist for modelling priority ruled intersections and freeway operations.

a The Isolated Intersection

The analysis by Webster (Ref. 42) and Webster and Cobbe (Ref. 43) form the basis of signalized intersection capacity analysis as applied in a number of jurisdictions. Both references outline methods of computing signal settings such that overall delays at the intersection are minimized (for critical

directions). The optimum cycle time (ie the cycle at which delays are minimized) can be shown to be (Ref. 42):

$$Copt = (1.5*L + 5)/(1 - Y)$$

Copt – optimum cycle time

L – lost time (all intergreen in which flow does not occur)

Y – sum of critical lane demand to saturation flow ratio for each phase – corresponds to the percentage of cycle time to clear critical approach volumes

The critical elements of the cycle time determination are the demand and the saturation flow. Demand is determined from a count of the intersection, while saturation flow, or capacity is determined by a detailed analysis of conditions at the intersection. It is possible to analyze intersection operation on a lane by lane basis, in contrast to network assignment models. The capacity of each lane directly accounts for signal phasing and intersection characteristics such as parking, geometrics and pedestrian flows. Ref. 18 provides detailed procedures for determining intersection capacity for Alberta conditions.

The optimal allocation of green times at a signal may be defined in several ways. A method often selected, for its simplicity, is the technique of balancing demand/capacity ratios for critical lanes of each phase. Other techniques used include balancing probability of clearance for critical lanes, or minimizing overall intersection delay. In each case, the models have been both theoretically justified and verified through application.

Methods exist for the assesment of both delays and queues, for a given set of signal timings. As these factors are considered to be important in the 'cost of travel' along a route, considerable effort has been put forth in the development of delay and queue models. A typical delay formula, which has been verified by field measurements in Edmonton consists of two parts; 'uniform' and 'random' delay.

Delay = Uniform (Du) + Random (Dr)

$$Du = (c(1 - h)^2)/2(1 - h*x)$$

$$Dr = 15*t/z \left((q - z) + \sqrt{(q - z)^2 + (240 * q/t)}\right)$$

where:

r – effective red time

g – effective green time

c – cycle length = r + g

s – discharge rate (saturation flow)

q – arrival rate (volume)

y = q/s

h = g/c

x = y/l (degree of saturation)

z = h*s (hourly capacity)

t – simulated time:

– length of time that q > z (oversaturated)

– length of simulation (undersaturated)

The uniform delay is that which would occur considereing queueing theory with a uniform arrival rate over the hour (Ref. 23). Random delay is intended to reflect the delay which occurs due to predictable fluctuations about the mean arrival rate. The formula presented here was derived by Whiting (Ref. 36). To calculate average queue lengths at an intersection, the total hourly delay (vehicle seconds) is divided by 3600 seconds per hour.

The analytical techniques for individual intersections have been developed into computer programs. One such program is the SINTRAL system (Ref. 38), which enables cycle time selection, green allocation and delay/queue analysis. SINTRAL is currently used extensively by both cities and consulting firms in Alberta.

b Network Models

When a signal is part of a network of interconnected, fixed time signals, the analysis becomes three dimensional. In addition to determining cycle time and green intervals, the relative offset of one signal with respect to others in the network must be determined. The typical network problem is reduced to a

system of links and nodes as shown in Figure 2.2. In contrast to network assignment models, turning movements, and bus movements are often coded as separate links.

One of the most widely used programs for network signal design and simulation is TRANSYT (TRAffic Network StudY Tool). The TRANSYT program was developed by D. Robertson of the British Transport and Road Research Laboratory (TRRL) in the late 1960's. The program algorithm uses a detailed and quite accurate model for simulating traffic movements in a network. Arrival and discharge patterns at signals (nodes) in the network are developed by considering the dispersal of vehicle platoons as they traverse a link connecting 2 nodes. Greater dispersion occurs on longer links. The resulting arrival and discharge patterns during one cycle are referred to as cyclic flow profiles. In addition to traffic simulation, an optimum set of timings can be determined by minimizing the network performance function. The performance function is quantified by:

P.I. = F(delays, stops)

The ability exists to separately model the movement of different vehicle modes, enabling the minimization of passenger delay by the program. Past experiences with TRANSYT indicate that predicted performance indicators agree well with measured values (Ref. 35).

May (Ref. 34) has developed an extension to the TRANSYT program that includes vehicle emissions and fuel consumption as a part of the performance index. This work has been modified and included into TRANSYT version 8, recently released by the Road Research Laboratory.

Delay simulation in network optimization models has been dealt with using a variety of techniques. In the TRANSYT 7 model, delays are split into uniform and random components. Uniform delays are computed directly from the cyclic flow profile for each link. Random delays are calculated from the Whiting formula, as outlined in the previous section. Queue calculations are performed directly after delays have been determined.

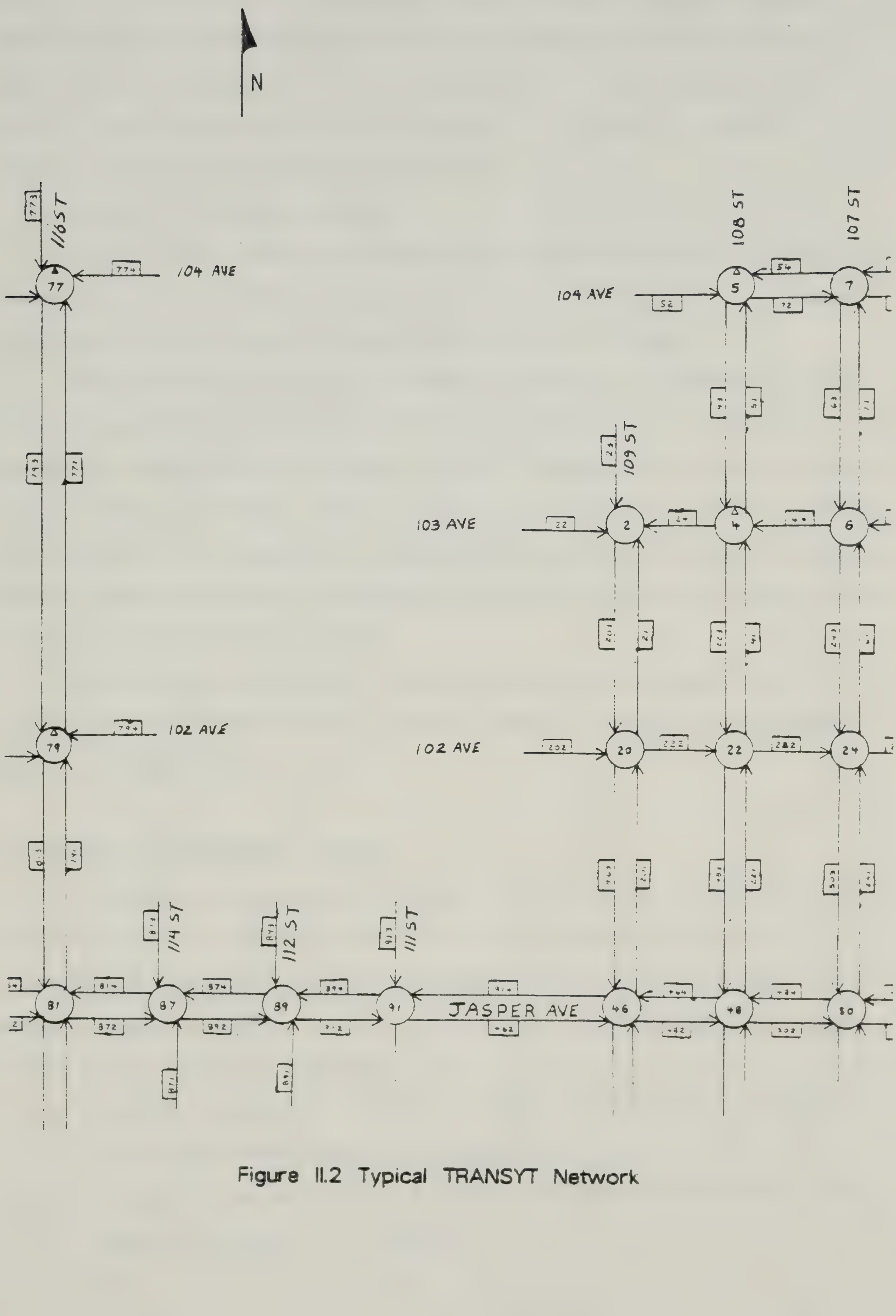


Figure II.2 Typical TRANSYT Network

In addition to TRANSYT, other network signal design models include SIGOP, SSTOP and the GLC Combination method. These models are designed to develop timings by minimizing delays and stops. Although they are useful for some practical purposes, the traffic representation in these models is not generally accurate enough to permit the model to be used for detailed simulation, in addition to detailed signal design.

c Limitations of Existing Methods

The preceding discussion indicates that traffic engineering techniques and models have developed to a point where refined methods exist for the design and analysis of both individual signals and networks of signals.

These methods, however, are limited to designing or evaluating on the basis of the volumes and network configurations that are provided. It is not possible to incorporate the possibility of flow re–assignment into any of these models, other than through manual estimation. As a result, only a partial analysis and comparison of transportation management proposals can be made. Secondary effects (such as relocation of congestion, 'shortcutting' traffic) can often not be anticipated or predicted in advance.

As with traffic assignment models, the techniques included here form only part of the development of a model capable of evaluating and predicting equilibrium changes in the network.

C. Optimization-Assignment Models

A number of researchers have been able to develop working models to analyze portions of a roadway network for the purpose of assessing transportation management plans. These models combine a level of detail used in network operations models with the ability to vary route selection. The models consist of two major components:

a. a traffic assignment routine that builds a network tree and loads flows such that travel time is minimized

b. a traffic operations model that evaluates signal delay and link travel times for flows in the network

c. models may include a routine to re-optimize signal timings after each of the previous steps are completed

Each of these steps are re-iterated until convergence occurs (usually after several passes through the model).

Three of the better documented models for urban arterial networks are discussed here. A number of other models related strictly to freeway corridors also exist, but these are not discussed here. It was felt that, for Alberta conditions, freeways do not form a major component of the transportation system, indicating that arterial based models are more suitable.

a University of California - Traffic Management Model

The extensions to the basic TRANSYT 6 package developed by May (Ref. 34) to evaluate the impact of improved signal settings on fuel consumption and vehicle emissions represented an initial step to evaluate T.S.M. proposals. A further extension to TRANSYT 6 was developed by May (Ref. 33), to consider possible route and mode change resulting from the implementation of optimized timings. These quantities are estimated by considering the response of drivers to a stimulus.

%Demand shift = Sensitivity*Stimulus

%Demand shift = % passengers shifted from one route or mode to another

Sensitivity = attractiveness to shift given by spare capacity on alternate routes, and availability and service quality of transit service

Stimuli = difference in travel time between alternate routes and modes

In references 28 and 34, a number of arterial traffic management strategies were compared for two routes: Wilshire Boulevard in Los Angeles, and San Pablo Avenue in Berkeley. The objective of these studies was to determine what strategy was able to minimize passenger delay, fuel consumption,

or other network performance indicator. In both cases, the use of the model was confined to a linear network. On the basis of the relative comparison between strategies, a preferred T.S.M. plan was selected.

The results of model evaluation provide a relative comparison between alternatives, but the actual magnitude of results may not be in a form that allows direct use. No detailed explanation of model parameters was given. As the use of this model is confined to linear networks, it would have only limited application to the evaluation of T.S.M. projects.

Recognizing these limitations, May has extended his work to the development of a model to simulate dense networks, such as residential areas or central business districts. The model, Micro-Assignment, is documented in Ref. 33, and is intended to permit the evaluation of T.S.M. strategies in very localized areas. Initial model results are provided in Ref. 33 for the San Jose, California downtown area, and for a residential area of the neighbouring community of Palo Alto.

For application to large scale T.S.M. projects, such as Project UNI evaluations, it would not be possible to use any of the models discussed here that were developed by May. The models for analyzing dense networks, however, appear to be more suitable than the other models that are presented in the following sections (CONTRAM, TRANSIGN), due to the representation of signal co-ordination and priority ruled intersections.

b CONTRAM

CONTRAM (CONtinuous TRaffic Assignment Model) was developed by the Transport and Road Research Laboratory in England to enable the prediction of the economic and environmental impact of various traffic management schemes (Ref. 29). The basic principles of CONTRAM are explained in the following section.

Vehicles are loaded onto the network by time slices, (ie 10 or 15 minutes), to enable the simulation of peaking behaviour. Within each time slice, vehicles in 'packets' of about 10 vehicles are successively assigned to the network, and travel via the shortest time path to their destination. Travel time, in

CONTRAM is taken as link free flow time plus queueing time at junctions (signal, roundabouts, priority ruled). This process is continued until all vehicles in a particular time slice have been loaded onto the network. After the loading of each packet, delays are updated.

The full loading of the network is performed for a number of iterations. In each case, the delays from the previous iteration serve as the starting point for the traffic assignment. After sufficient iterations, an equilibrium assignment should result (although the program does not guarantee an equilibrium assignment).

CONTRAM also has the ability to re-calculate signal timings based on the results of the traffic assignment (using the British methodology). In this way, both vehicle assignment and signal capacity can be optimized simultaneously. At present, the model can only perform a single re-calculation of signal timings, after the first full network loading. Work is currently underway to enable the re-calculation of signal timings after each iteration of the traffic assignment.

CONTRAM represents a major advancement in the ability to model T.S.M. strategies. The ability to simultaneously adjust assignment and network assignment (signal timings), while analyzing flows at an operations level of detail represents a major improvement over previous models. The calculation of delays and queues by time interval also enables an accurate assesment of saturated conditions.

Several limitations in the use of CONTRAM remain, however. Some of these limitations are listed below:

a. CONTRAM is designed for the evaluation of traffic management plans. As such, an evaluation of T.S.M. schemes involving more than one mode (ie bus lane, bus priority) cannot show changes in mode selection.

b. Origin-destination data is fixed, meaning that temporal re-assignment cannot be modelled.

c. Signal co-ordination cannot be adjusted by CONTRAM. For application to dense networks of signals (ie the CBD), this would require a simultaneous use of CONTRAM and TRANSYT.

c TRANSIGN

The origins of this model are described in a number of papers (Ref. 6,7,12,13) by Allsopp and Charlesworth. In Ref. 7, it was recognized that traffic signal settings could affect traffic assignment, and that a network optimum might not correspond to the case of drivers minimizing their own travel time.

Charlesworth, of the University of Newcastle, has developed a working model entitled TRANSIGN, which combines an equilibrium assignment model 'TRAFFIC' and a signal optimization model 'TRANSYT'. TRAFFIC is an equilibrium assignment model developed by Florian (Ref. 22) and tested in Winnipeg (see section 2.2). The network description uses a link-node representation, that permits the same network format to be used for both 'TRAFFIC' and 'TRANSYT'.

An iterative procedure is used by TRANSIGN; initially assigning traffic, and then optimizing signal settings. This routine is repeated, until steady state conditions are arrived at after 5 to 10 iterations. Ref. 13 indicates that the size of traffic management scheme being studied may alter the level of detail selected for the network evaluation. As an example, more detail would be used in dense networks such as the CBD. No discussion of simulation of priority ruled intersections was provided.

A major advantage of TRANSIGN is the modelling of vehicle platoons through the use of the traffic model from TRANSYT. Other important features of TRANSYT, such as the ability to model bus movements and shared stoplines, can be included in the simulation. The model does provide an extension to the TRANSYT simulation model to enable the simulation of freeway operations.

No detailed examples of TRANSIGN were provided in any of the references reviewed, so all limitations of the model are not known. The program descriptions reviewed to date appear to indicate the following limitations:

a. The use of the 'TRAFFIC' assignment routine in saturated networks has not been discussed in any of the references examined. As a result, it is uncertain whether realistic delays are being predicted.

b. Flows are un-constrained at bottlenecks (ie not accumulated), and the time to disperse queues is not considered.

c. The simulation period considers flows over the entire peak hour, rather than performing the analysis in a number of time intervals. As a result, the model cannot be used to predict peaking behaviour.

d. The use of TRANSYT to determine signal settings requires the use of a common cycle time throughout the network. This may restrict the program flexibility in large networks.

e. As with CONTRAM, T.S.M. strategies that involve either a change in mode, or a change in origin–destination data cannot be evaluated.

d Comparison

As indicated, the three techniques discussed above represent some of the more well documented programs for the analysis of T.S.M. strategies. One limitation, common to all models of this type, is a lack of testing and application with real traffic networks. It also appears, based on this discussion, that problems remain in the treatment of saturated networks. The current state of T.S.M. modelling was well stated by Charlesworth (Ref. 13):

> "there exists no technique at the present time which combines the advantages of a mathematically rigorous assignment method with the ability to deal properly with time dependence and overloads"

Each of the models described in this section dealt only with route assignment, with the exception of May's model, which incorporates modal choice. Due to the nature of the input (fixed origin – destination table), none of these models can be used to assess the variation of traffic demand over time (temporal re–assignment). Thus, the ability to simulate T.S.M. strategies such as peak hour pricing, flexible working hours, or the introduction of extreme congestion during part of the peak cannot be evaluated.

In summary, then, the models presented here do not represent a complete solution to the problem of assessing transportation management strategies.

D. Other Aspects of Equilibrium

a Travel Budget Theory

In Economic Theory, time can be viewed as a scarce commodity, as only a limited number of hours per day are available. One could expect, therefore, that the hours spent per day in travel would not exceed some upper limit. Beyond this limit, insufficient time would be available for other activities.

In an individual's journey to work, one would expect equilibrium flow patterns to develop in recognition of this 'travel budget'. At the same time, a change in network conditions would be expected to result in the development of a new equilibrium. It could be anticipated that people would behave in such a way that their time spent travelling is kept constant. Any increase in peak route travel time might be expected to shift non-work trips to some other time. In this way, the total time spent travelling would remain constant. The effect of a network capacity loss might then be:

a. route re-assignment, as travellers attempt to reduce travel time to previous values

b. if route re-assignment is not sufficient, then temporal re-assignment would next occur so that travel time is reduced by travelling at a time other than the peak

c. modal switching might be considered if neither of the above succeed in reducing travel time to an acceptable value

Chumak and Braaksma (Ref. 15) present the results of research conducted in several Canadian cities which indicate a remarkable similarity in the amount of time that persons are willing to devote to travel. For both Canadian and American cities, an average of 1.1 hours are devoted to travel.

This concept leads, intuitively, to a more complex view of travel decision making. The traditional traffic assignment model has not yet made extensive use of this concept. Viewed in a more long term context, travel budget theory has implications for both the land use and structure of the city. For example, the construction of a new transportation corridor would be expected to result in a change in the land use along this route.

b Temporal Re-assignment

In the literature reviewed by this author, the only discussion of temporal re-assignment noted was in the context of evaluating flex-time proposals. Alfa and Minh (Ref. 4) present a model for determining the peaking behaviour of traffic. Costs are attached for delay, and for early or late arrivals. A peak profile is determined by successively attempting to reduce costs from an initial state, where all traffic tries to arrive at the destination at the same time. In the case of flex-time, a broader and less peaked peak period is projected. The approach presented by Alfa and Minh appears reasonable, but no practical applications of this model were noted.

In examining the current 'state of the art' in T.S.M. modelling, Horn (Ref. 25) notes that a French model (THESEE SATURATION) is able to re-assign demand in both space and time. No other discussion of this model was noted.

c Equilibrium Studies

Surprisingly few studies were noted in this literature review where 'before' and 'after' equilibrium states are compared in a network. Only two studies were found where attempts to track the development of a new equilibrium through flow monitoring had been made.

Levin and Brewer (Ref. 30) used linear regression to study the change in equilibrium following the introduction of ramp controls on a freeway in Houston, Texas. Volumes on three parallel arterials, together with the freeway facility, were monitored after the network change. A period of six study days was required to re-establish equilibrium in study area, as defined by linear regression. Unfortunately, this article did not indicate the magnitude of route volume shifts, travel time or queueing 'before' and 'after'.

Yagar (Ref. 44) studied the impact of opening a new link in the roadway network of Kitchener, Ontario. It was concluded that most users decided upon their final routes within a week after the opening of the new facility. This equilibrium study was restricted to an evaluation of volumes on two parallel routes following the opening of the new facility. Some evidence of overall volume increases due to route re-assignment from other corridors was

presented. No discussion of altered network travel times or other details of the equilibrium change was presented.

E. Summary of Existing Research

In the preceding sections, a summary of current studies and models related to network equilibrium and T.S.M. evaluation have been presented. This literature review is not considered exhaustive, but does present a cross-section of available techniques.

The examination of models here appears to indicate that additional development and research will be required before these techniques can be used for evaluating T.S.M. strategies. Model limitations fall into two general categories; the examination of travel behaviour and network state.

1) Network State

a. Conventional traffic assignment models do not examine arterial networks in a sufficient level of detail to permit the assessment of many T.S.M. strategies.

b. Traffic Operations techniques are required to enable sufficient detail for an accurate assessment of intersection and network operation. These methods are required to calculate travel time, delays, queues and capacity.

c. All assignment models examined here considered only travel time and intersection delay in their determination of equilibrium flows.

2) Travel Behaviour

a. Traffic assignment models are able to predict route selection for given network travel times. Efficient algorithms exist for determining equilibrium assignment.

b. A theoretical model exists to predict the temporal assignment of traffic caused by congestion and the cost of early or late arrivals.

c. The Travel Budget concept indicates that average daily travel time is a constant. This implies that a change in network state may result in more than route re-assignment, if the travel budget would be altered

as a result.

The relationship between travel behaviour and network state must be understood before any techniques can be generally applied to the assessment of T.S.M. strategies. The development of combined operations and assignment models is an attempt to relate these two factors. Additional reasearch and model development is needed before these models can be effectively used in T.S.M. evaluations. The current state of these models is:

a. All operations and assignment models examined here can only deal with route re-assignment resulting from travel time and capacity changes.

b. No models or techniques were found that considered the influence of network factors other than travel time and delay on flow assignment.

c. Temporal or modal re-assignment, as a consequence of a network change has not been well studied.

d. The application of any of these models for T.S.M. evaluation has been primarily restricted to research using hypothetical examples. Little testing of these models against actual traffic situations has been reported.

III. STUDY LOCATIONS AND PROCEDURES

A. Study Locations

In order that the thesis objectives could be met, it was necessary that field measurements of factors affecting equilibrium, and changes in travel behaviour be undertaken. The only way that this could be done was through the measurement of travel behaviour 'before' and 'after' a change in the capacity of the road network. After the network change occurred, the establishment of a new equilibrium was observed through daily monitoring of flows, queues and delays.

In spring, 1979, all traffic management schemes proposed for 1979 implementation in Edmonton were reviewed, to determine which locations would be most suitable for study. The selection of study locations was based on the following criteria:

a. The only network change permitted within the study area was that being assessed in the equilibrium study. This excluded areas where road construction or detours disrupted either 'before' or 'after' traffic in the study area.

b. A variety of projects, providing a range of impacts from localized to area-wide, were required.

c. Locations being studied had to consider both capacity improvement and capacity loss.

d. Only projects where significant delay and queueing impacts were expected were considered as candidates for study.

e. Study areas were selected with consideration of the manpower available.

Manpower used for data collection involved personnel from the City of Edmonton, Engineering Department and Transportation Systems Design Department. These were supplemented by graduate students from the University of Alberta. Limited resources made it possible to study only 3 locations in 1979. Locations selected were: Fort Road – 66 Street, Kinnaird Bridge detour and Stony Plain

Road – 142 Street. The study locations within Edmonton are shown in Figure 3.1. The roadway networks affected by each traffic management scheme are shown in Figures 3.2, 3.3 and 3.4.

a Fort Road and 66 Street

The Fort Road – 66 Street. traffic management plan, shown in Figure 3.5, was implemented on July 11, 1979. This scheme introduced the following changes to improve capacity and reduce delays at this congested intersection:

a. Westbound left turns on Fort Road at 66 Street were banned, and a left turn rerouting scheme was introduced.

b. Signal phasing was simplified from 3 full phases (separate phases for eastbound and westbound), to a simultaneous green for east and west, preceded by an advance phase for eastbound left turns.

c. The proportion of green time for critical northbound and eastbound flows was increased (as a result of the simplified signal phasing).

For 'before' conditions, the most severe congestion occurred in the PM peak. Intersection analysis using the SINTRAL system also indicated that the PM peak period would experience the greatest reduction in delays, after the implementation of the traffic management plan. For this reason, the PM Peak was selected for study, in recognition that the mixture of work and shopping trips would complicate the 'before' and 'after' comparison.

b Kinnaird detour

In May, 1979, the Kinnaird Bridge on 82 Street, south of 112 Avenue, was closed to permit deck replacement. This bridge carried AM peak flows in excess of 1200 vehicles per hour in the critical southbound direction. As a result, a major impact to volumes and delays on adjacent arterials was expected.

To minimize the most serious impacts of the closure, an initial estimate of flow re-distribution was determined. This indicated that a number of control changes would be required in the area. These changes, shown in Figure 3.6 included:

a. timing changes at a number of intersections in the area

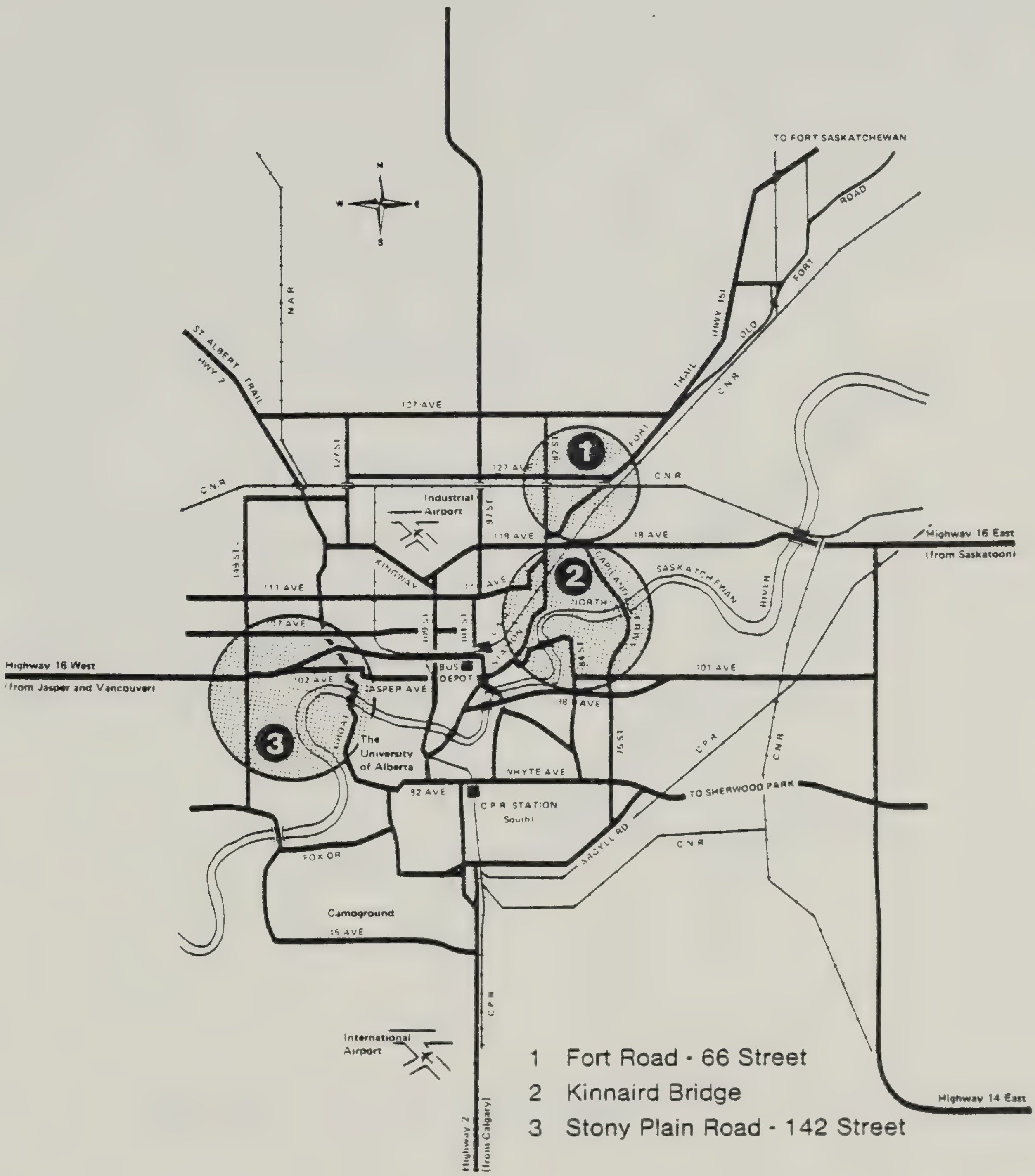


Figure III.1 Study Areas in Edmonton

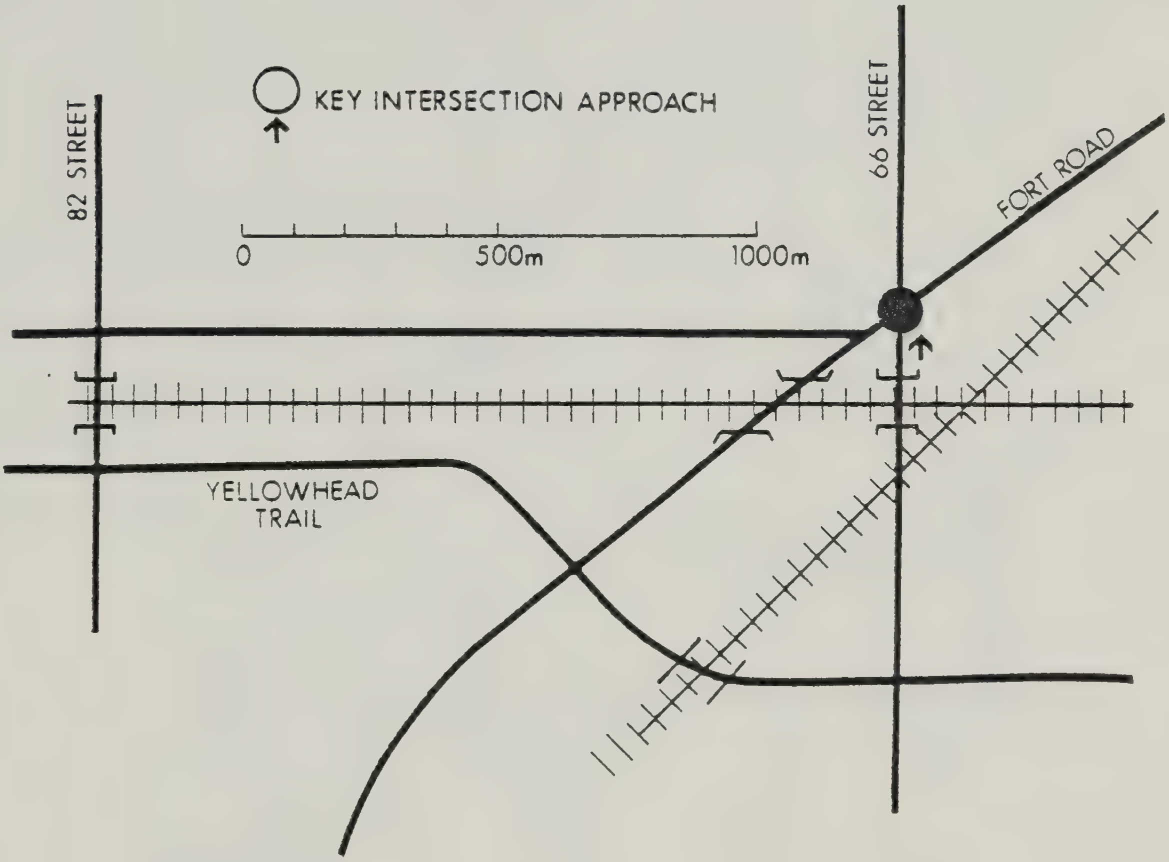


Figure III.2 Fort Road and 66 Street

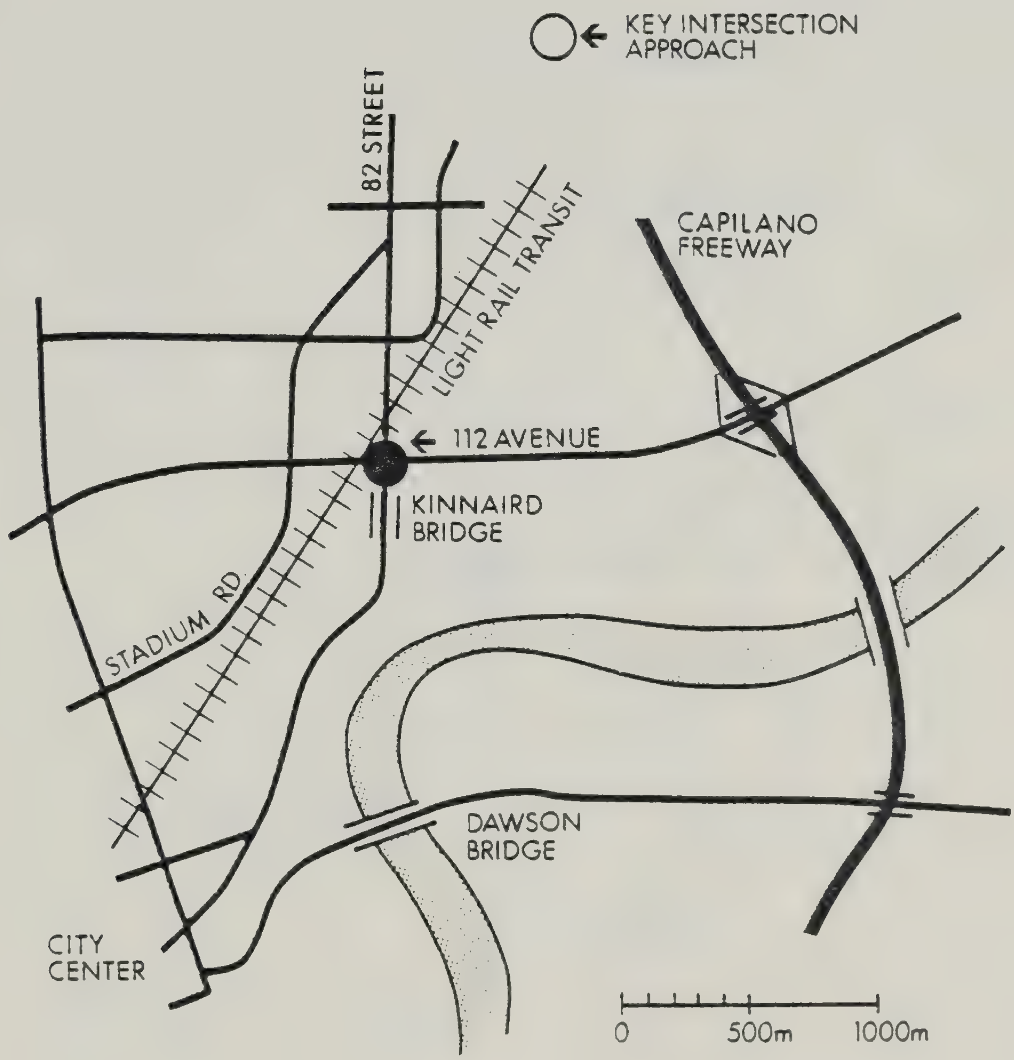


Figure III.3 Kinnaird Bridge

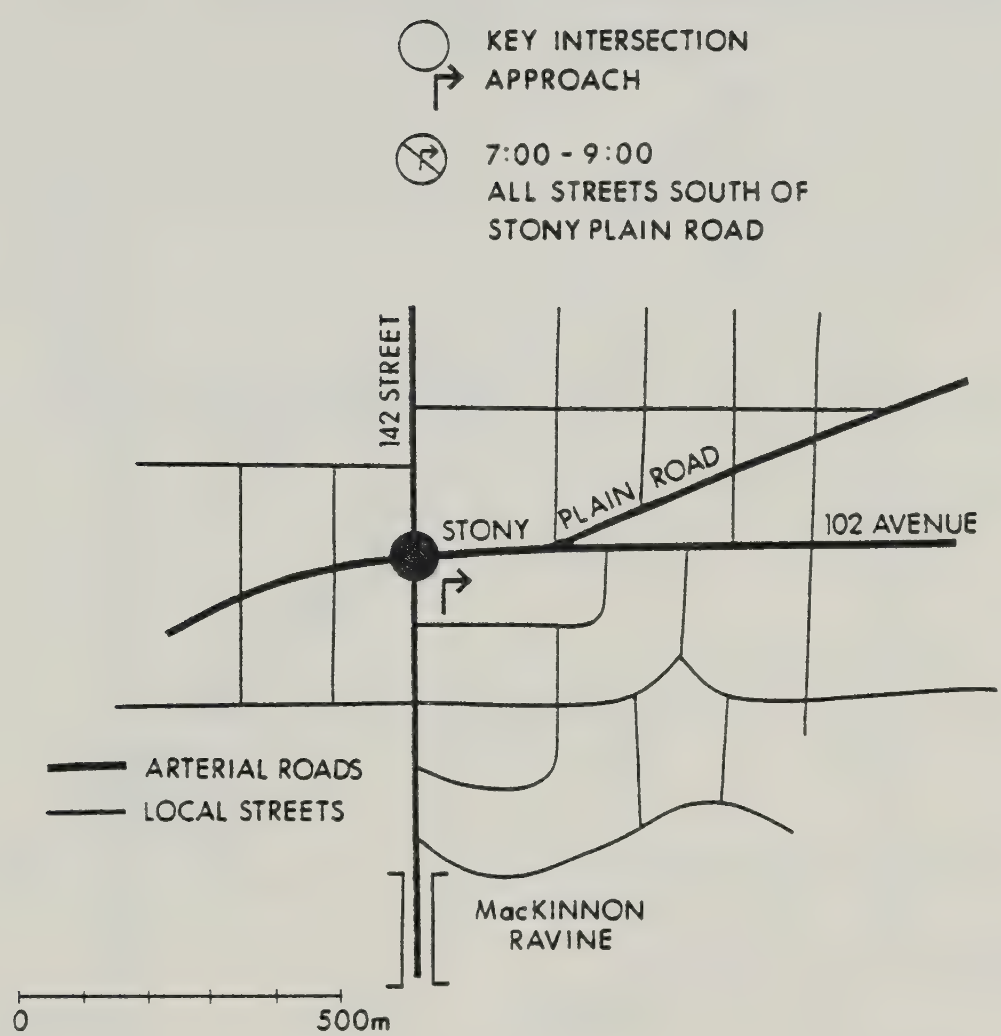


Figure III.4 Stony Plain Road and 142 Street

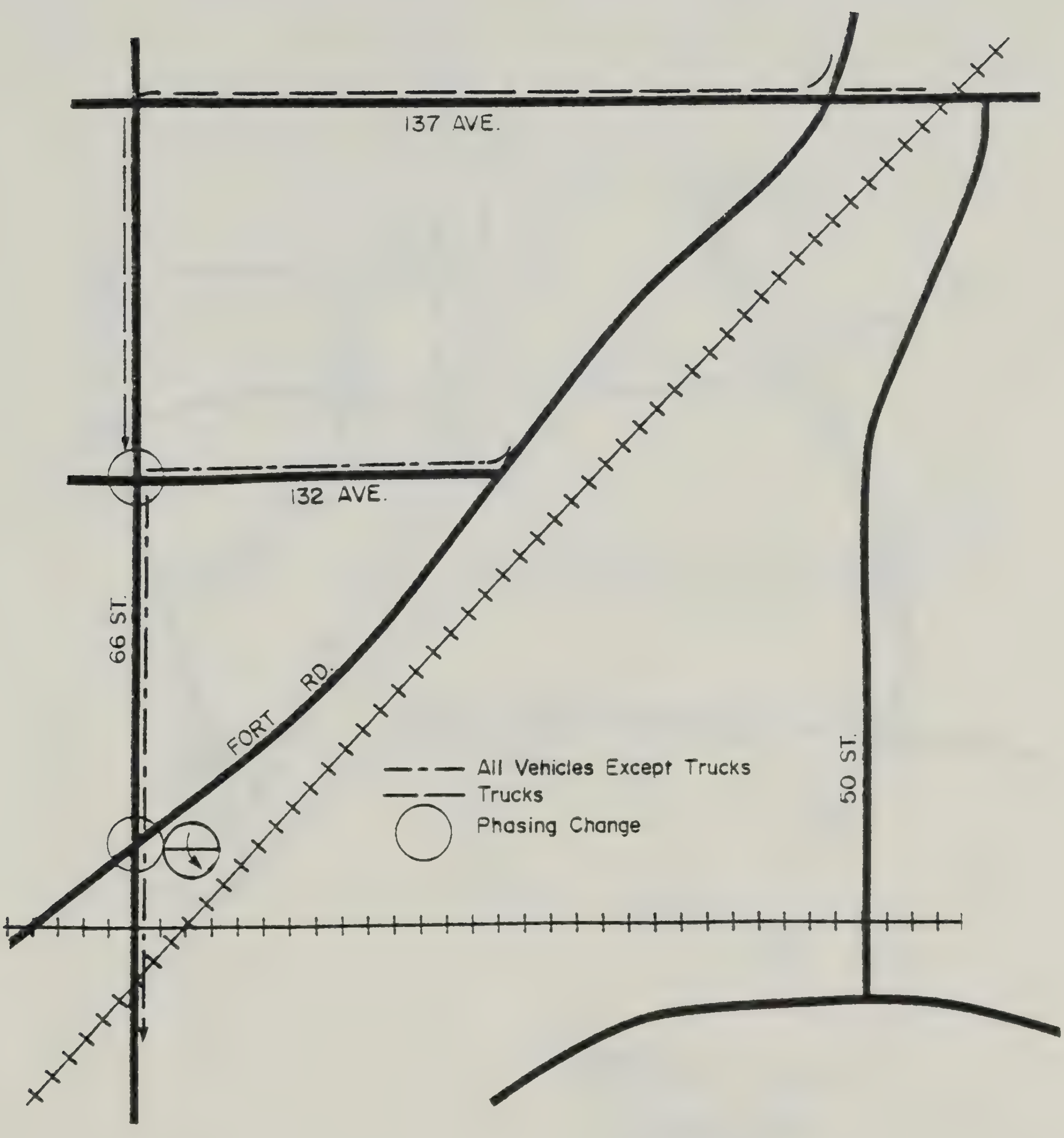


Figure III.5 Fort Road and 66 Street Traffic Management Scheme

Figure III.6 Kinnaird Detour Network Changes

b. restrictive signal timings on 82 Street, and on 112 Avenue to prevent blockage of the L.R.T. crossings in the area.

c. closure of the left lane of 112 Avenue westbound, east of 82 Street.

To accomodate detoured traffic, signed detour routes directed traffic to use Stadium Road, as this was the closest artery parallel to 82 Street. Capacity analysis indicated that the 112 Avenue – 86 Street signal would be overloaded, resulting in a diversion of trips to routes further away than Stadium Road. In anticipation of flow shifts, signal timings along both 95 Street and 106 Avenue were altered to increase capacity for detoured traffic along these routes.

Conditions prior to the closure, during both peak periods, were relatively uncongested. With the closure of Kinnaird Bridge, significant capacity problems were anticipated in both peaks, particularly at 112 Avenue – 86 Street. The morning peak was selected for study in this area, as this time period was expected to show the largest increase in congestion. The morning peak traffic consists mainly of home to work trips, which were expected to give a better 'before' and 'after' comparison than PM peak traffic.

c Stony Plain Road and 142 Street

In the fall of 1979, a number of changes were introduced on radial arterials from the downtown to the west end of Edmonton, in order to improve traffic flows. Congestion in this area was focussed on the Stony Plain Road – 142 Street intersection. Congestion at this location had grown more severe over a number of years, and was resulting in 'shortcutting' traffic problems on residential streets in the area.

The most severe congestion 'before' occurred during the morning peak period. As the traffic improvements were expected to produce higher delay savings during the morning peak, this time period was selected for study.

The key network change in the area, to implement the west end imporvements occurred at the Stony Plain Road – 142 Street intersection, where the following improvements were made:

a. The Stony Plain Road – 142 Street signal was placed on computer

control. The westbound delayed left turn phase was deleted in the morning peak period to provide more green time to critical northbound and eastbound flows.

b. Additional lanes were provided along Stony Plain Road between 142 Street and 139 Street. This enabled the implementation of a northbound double right turn off 142 Street, and a double left turn onto Stony Plain Road at the junction with 102 Avenue.

c. The nearby intersection of Stony Plain Road - 102 Avenue was signalized.

At the same time, minor improvements were made at other signals in the area to accomodate the expected higher flows through Stony Plain Road and 142 Street. These changes consisted of signal timing revisions, pavement marking alterations and signage changes. Improvements were made at all signalized intersections between 124 Street and 156 Street along 107 Avenue, 102 Avenue and Stony Plain Road.

B. Data Requirements

The data collected in each of the studies was intended to meet the objectives outlined in Chapters 1 and 2. The data collection enabled the definition of network state 'before' and 'after' the implementation of traffic management plans. An accompanying study of travel behaviour enabled a better understanding of the 'before' and 'after' equilibrium states. The development of a new equilibrium was monitored through a daily count of one or more intersections in each study area, following the introduction of the network change.

a Network State

For 'before' and 'after' conditions, the following measures of network state were examined:

a. vehicular delay

b. queue length

c. general observations of driver behaviour

b Travel Behaviour

Only three aspects of travel behaviour could be assessed due to the short length of time between 'before' and 'after' comparisons. Changes in route selection, temporal assignment (peaking) and mode selection were examined. Mode selection was only studied for the Kinnaird area, as this was the only location where changes in comparative auto and transit travel times were expected.

c Network Equilibrium

To examine the relationships between travel behaviour and network state, more than a 'before' and 'after' comparison was considered necessary. To gain a better understanding of the development of network equilibrium, flow data was collected immediately after a network change was introduced. Intersection flows were monitored continually, until it was clear that no further volume changes would occur. The assessment of when flow stability was established was based on a judgement of the situation. In no case, however, were less than two weeks of data collected before the commencement of the 'after' study of network state and travel behaviour.

C. Determination of Study Areas

Prior to beginning data collection, the study areas had to be defined. A review of literature revealed no procedures to permit an assessment of the size of the study area. As a result, study areas were established using empirical methods. The area studied was intended to include a large enough section of the network that few trips would be shifted outside the study area. The area also was intended to include all locations where a change in network characteristics or flows was expected. The following procedures were used to define study areas for the three locations examined.

a Fort Road - 66 Street

The delay reductions in the PM peak, at this location, were anticipated to be large enough to attract traffic to either Fort Road or 66 Street northbound, from alternate routes across the C.N.R. screenline. The closest routes were considered; 82 Street, and 50 Street. These routes represent the nearest railway

crossings east and west of Fort Road and 66 Street. Intersections adjacent to the C.N.R. railway crossings generally form the major bottleneck in northeast Edmonton for northbound traffic in the PM peak. The study area (Figure 3.2) was extended south to Yellowhead Trail, in order to include a major turning movement from the east to the north. This flow was expected to cause increased flows on 66 Street, and reduce traffic volumes on 82 Street.

b Kinnaird Bridge

Congestion at the 112 Avenue – 86 Street intersection (on the main detour route) was expected to cause traffic diversion to 95 Street and 106 Avenue. Some diversion to 96 and 97 Streets was also considered, but 97 Street was felt to be predominantly serving flows from a different area of north Edmonton. Including this major flow would have caused a major expansion in data collection, with little difference in the final results. 118 Avenue was also considered as a possible alternate route for traffic that used 112 Avenue westbound before the bridge closure.

As a result, the study area, shown in Figure 3.3, was confined to 118 Avenue on the north, 96 Street to the west, the Capilano Freeway to the east, and 106 Avenue on the south.

c Stony Plain Road and 142 Street

The combination of measures to improve traffic flows eastbound along the Stony Plain Road – 102 Avenue corridor was expected to cause a flow shift to this corridor from other east-west corridors in west Edmonton. The nearest parallel corridors are 107 Avenue, to the north, and Whitemud Freeway/Keillor Road to the south. The study area boundaries, shown in Figure 3.4, included all major intersections between 149 Street in the west and 124 Street in the east, between Keillor Road and 107 Avenue.

D. Methodology

a Intersection Studies

Each study area was comprised of a network consisting mainly of arterial roadways. As a result, the network equilibrium states were governed primarily by the operation of signalized intersections. The primary performance indicators at signalized intersections are vehicular delays and queueing. As a result, the major task of data collection to assess network operation was concentrated on the measurement of these two parameters.

A measurement of total vehicular delay at a signal is generally only possible using time lapse photography, which was not available for this study. The 'time in queue' delay serves as a close approximation to approach delay, but is again difficult to measure directly. As a result, delays were deduced from queue length measurements, using a technique documented by Sagi and Campbell (Ref. 37).

Using queueing theory, (Ref. 23) it can be shown that vehicular delay is equivalent to the area under a curve of queue length versus time. Sagi and Campbell (Ref. 37) determined that recording queue length in each signal cycle (at start of green and start of red), together with a record of discharge per cycle provides enough information to calculate delays. If queue length and discharge during each cycle are known, the 'time in queue' delay can be determined directly. A representation of typical queueing patterns for undersaturated and saturated intersections are shown in Figures 3.7 and 3.8. Delays are computed as follows by the method of Sagi and Campbell:

$$\sum_{j=1}^{M+K} Dj = R/2*(\sum_{j=1}^{M} Qj + \sum_{j=1}^{K} Vj) + C*\sum_{j=1}^{K} A(j-1)$$

where:

Dj – total delay (veh*sec) over j cycles

M – number of undersaturated cycles

K – number of oversaturated cycles plus undersaturated cycles with queue at start of red

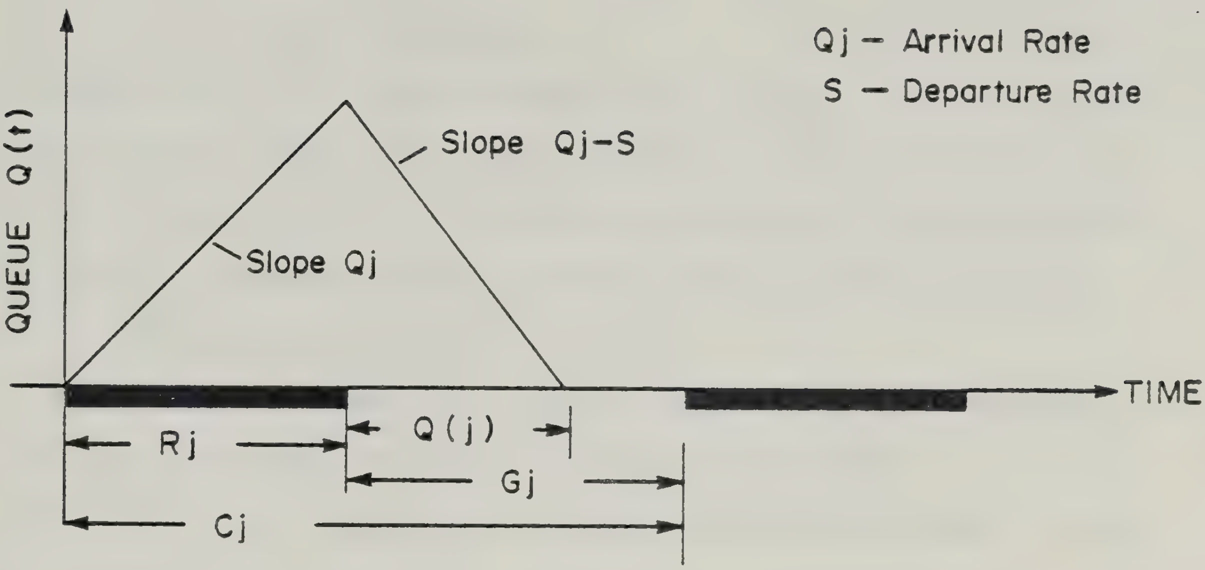


Figure III.7 Queueing Patterns at an Undersaturated Signal

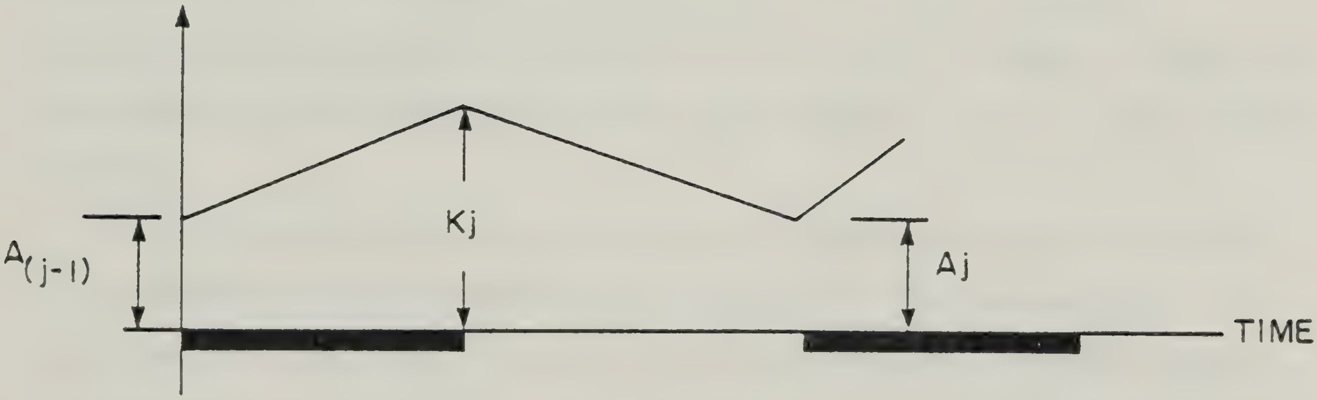


Figure III.8 Queueing Patterns at an Oversaturated Signal

Q_j – queue at start of green for jth undersaturated cycle

V_j – discharge on the jth oversaturated cycle

$A(j-1)$ – queue at start of previous red phase for cycle j

C – cycle length (sec)

R – effective red interval

Average delay = D_j / total discharge for j cycles

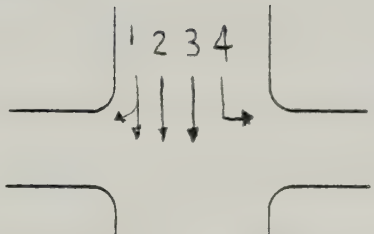
This formula assumes that in an undersaturated cycle, vehicles are delayed, on average, for one half the effective red interval. This corresponds to random arrivals. For saturated cycles, vehicles in queue at start of red are assumed to have a one cycle delay.

This formulation is based on a fixed time signal. The traffic actuated signal may also be studied, but the delay must be determined on a cycle by cycle basis, rather than using average effective red and cycle length, for the simulation interval.

To apply this methodology to field surveys, a lane by lane, cycle by cycle record of discharge and queues is required. The data sheet shown in Figure 3.9 was used for surveys in all three network areas that were studied. At traffic actuated signals, a record of cycle by cycle timings must also be maintained. To ensure an accurate calculation of delays, the start of signal timing surveys must be co-ordinated with the start of queue and discharge measurement. The experience of this study was that queue lengths in excess of 25 vehicles per lane cannot be counted by an observer who was also counting discharge.

Initially, long queues were measured by accumulating arrivals at the rear of the queue during time intervals of 30 seconds or one minute. Initial experience with this method indicated that a cumulative error occurred, due to vehicles entering or leaving the route between the rear of the queue and the intersection (ie 'shortcutting' traffic). The magnitude of error (up to 100 veh/hr meant that an alternate method had to be used. In cases of queues exceeding 25 vehicles per lane, an estimate of queue length using a known reference point (such as light poles or block lengths) had to be used, with another

Page 1 of ___



Cycle by Cycle Discharge and Queue Length

Location Stony Plain Rd - 142 St

Approach West

Date Nov. 22, 1979

Surveys by H. W.

Time Surveyed 7:00 - 9:00

Comments ___

Cycle No.	Queue-Start of Red			Queue-Start of Green			Cycle by Cycle Discharge				
	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3	Right on Red	Lane 1	Lane 2	Lane 3	Lane 4
1		0	0		1	0			3	3	
2		0	0		5	2			14	9	
3		0	0		3	2			11	7	
4		0	0		8	6		B	13	13	
5		0	0	1	3	5		2B	9	13	
6		0	0	1	5	5		B	12	11	
7		0	0		5	11			10	19	

Figure III.9 Data Sheet for Intersection Studies

observer recording discharge.

Some difficulty was noted with the interpretation of queue lengths at the start of red. For all surveys in this study, queue at start of red was taken to include both of the following; a) all vehicles who were present at the start of green and did not clear, plus b) any vehicles who arrived during green, came to a full stop, and did not clear.

Under extreme congestion, filming had to be used to capture queue lengths and delays. Delay filming from a helicopter was used to capture Day 1 of the Kinnaird closure. This was necessary due to extremely long queues in the area that could not be measured by an observer on the ground. At Stony Plain Road - 142 Street, a film of 'before' conditions was taken from the top of Crescent Place Apartments. From this vantage point, queue lengths exceeding one half mile could be measured.

b License Plate Surveys

Direct measurements of route selection and peaking behaviour were made using vehicle license plate surveys, for Fort Road - 66 Street and Kinnaird Bridge. In the Stony Plain Road - 142 Street area, it was not possible to conduct license plate surveys due to manpower limitations.

Observers recorded vehicle license plates, for all traffic passing a survey station, using cassette recorders. The time was recorded at the end of each 5 minute interval throughout the survey. The experience of this survey was that one observer was able to record volumes up to 800 vehicles per hour with minimal error, under average traffic speeds (40 km/hr). Higher volumes (up to 1100 per hour) were recorded under congested, 'stop and go' operation.

Using license plate data, it was possible to establish the routeing of vehicles through the network by comparing vehicles passing each survey station. A comparison of 'before' and 'after' data traffic passing the same survey station was also made use of. This data provided an indication of changes in route selection.

'Before' and 'after' comparisons of the time selected for travel in the network were also conducted. This was performed in two stages. Surveys on

successive days under 'before' conditions were performed in order to establish typical fluctuations in the time of travel of vehicles in the network. The 'before' and 'after' vehicle match was then compared to the typical daily fluctuation in order to establish if a significant shift had occurred in the time the trip was made.

Unfortunately, errors in license plate surveys are cumulative. The past experience with license plate surveys in Edmonton (comparing data between two stations), was that errors of at least 20% can be expected in the data collection and decoding process. The studies performed here involve matching paths through up to 4 or 5 survey stations, which would significantly increase errors. 'Before' and 'after' license plate comparisons were expected to further reduce the proportion of vehicles that could be matched, both due to different vehicle sets, and recording errors.

c Mode Selection

It was felt that Kinnaird was the only study area where a significant change in relative auto and transit travel times occurred between 'before' and 'after' conditions. This observation, coupled with manpower limitations meant that mode selection data could only be collected for the Kinnaird Bridge area.

In the Kinnaird area, the Northeast Light Rail Transit line forms the primary transit corridor. A daily record of morning peak (6:30 - 9:00) transit ridership was collected by LRT fare collectors. The data was collected for a period between two weeks 'before' the road closure and one week 'after'.

d Other Observations

General intersection observations were conducted at the same time as intersection surveys were performed. This was intended to indicate factors affecting network operation and travel behaviour that could not be directly measured. This included:

a. incidents (accidents, stalled cars)

b. critical incidents (illegal maneuvres, unsafe or erratic driver behaviour)

c. traffic pressure

E. Data Collection and Analysis

a Intersection Studies

'Before' and 'after' counts were conducted at all major arterial intersections within each study area where it was felt that significant flow or delay changes would occur. At the key intersections of the study areas (ie 112 Avenue – 86 Street and Fort Road – 66 Street), daily counts were conducted after the changes were introduced to monitor the restoration of equilibrium. In the case of Kinnaird, daily counts were also conducted at key intersections along the secondary detour routes (ie 111 Avenue – 95 Street and also 106 Avenue – 84 Street). These daily counts were continued until it was clear that no further volume shifts or peaking changes were occurring.

Data was analyzed using a combination of manual techniques and computer analysis. Computer analysis of discharge, delays and queues was only performed at locations experiencing saturated operation during a portion of the peak.

The computer analysis of intersection survey results made use of two programs; DFIX and DACT, for fixed time and traffic actuated signals, respectively Full documentation of imput formats and execution instructions for these programs is available in Resource Documents. Program inputs are:

a. location description
b. queue length at start of red and start of green
c. signal timings (fixed time)
d. cycle by cycle signal timings (traffic actuated)
e. number of simulation intervals, and minutes and cycles per interval

Analysis was normally performed on a lane by lane basis, with up to three movements (ie left, through, right) being permitted in one lane. with only the relationship between travel times and route In the case of fixed time signals, delays were averaged over the duration of the simulation interval. For traffic actuated signals, delays were accumulated over each cycle of the simulation interval.

Program outputs are:

a. echo – check of input timing information and location description
b. delay (veh sec) and average delay (sec/veh) for each interval
c. demand and discharge for each movement (ie left, through or right) per time interval
d. maximum queue per time interval

Sample program outputs from DFIX and DACT are shown in Figures 3.10 and 3.11. For saturated intersections with fixed time signals, lane saturation flows may be directly determined using average discharge per cycle.

Computer time requirements for DFIX and DACT are minimal. A typical analysis would require 1 to 2 seconds with the University of Alberta Amdahl 470 V–8 computer.

b Vehicle Travel Behaviour

License plate survey stations for the Fort Road – 66 Street and Kinnaird study areas are shown in Figures 3.12 and 3.13. A total of over 20000 vehicles were followed in the 4 license plate surveys that were conducted. 'Before' and 'after' surveys each covered a period of two hours during peak periods.

Following the surveys, the data was manually decoded from tape recorders to survey forms. The forms were, in turn, keypunched and transferred to computer disk storage for analysis.

The analysis of license plate data utilized three computer programs written by Doug Hunt, who was an undergraduate student in Civil Engineering at the University of Alberta, at the time of this research. Documentation for each of these programs is available. A brief description of the programs is provided below:

Route Selection - Programs PLPS and PLPSN

These two programs were used to examine flows along a route in the network. For program PLPS, only exact license plate matches are accepted, while for PLPSN, the user specifies the number of characters that will be accepted as an exact match. At each station along the route,

FIXED TIME SIGNAL DELAY COMPUTATION
SAGI AND CAMPBELL METHOD

LOCATION: Fort Road - 66 Street
APPROACH: EBD Curb Lane
DATE AND THE OF SURVEY: Tuesday, July 17, 1979 4-6 pm
COMMENTS: Day 5
CYCLE LENGTH: 100.Sec.
NUMBER OF CYCLES PER INTERVAL: 6
EFFECTIVE GREEN: 54 Sec.
MINUTES PER INTREVAL: 10

DISCHARGE PER MOVEMENT FOR EACH INTERVAL

INTERVAL	RIGHT	THROUGH
1	24.00	35.00
2	27.00	59.00
3	23.00	56.00
4	14.00	47.00
5	15.00	81.00
6	19.00	78.00
7	5.00	86.00
8	31.00	58.00
9	28.00	49.00
10	21.00	50.00
11	17.00	44.00
12	17.00	27.00
TOTALS	241.00	670.00

LANE DELAYS, DEMAND AND DISCHARGE FOR EACH INTERVAL

INTERVAL	DISCHARGE (per interval)	DEMAND	TOTAL DELAY (veh/sec)	AVERAGE DELAY (sec)	LOADED CYCLES	MAX. QUEUE	MAX PER CYCLE DISCHARGE
1	59.00	59.00	368.00	6.24	0	7.00	13.00
2	86.00	86.00	506.00	5.88	0	7.00	20.00
3	79.00	79.00	552.00	6.99	0	7.00	18.00
4	61.00	61.00	368.00	6.03	0	5.00	14.00
5	96.00	96.00	943.00	9.82	0	11.00	21.00
6	97.00	97.00	736.00	7.59	0	10.00	20.00
7	91.00	91.00	828.00	9.10	0	10.00	17.00
8	89.00	89.00	621.00	6.98	0	6.00	20.00
9	77.00	77.00	529.00	6.87	0	8.00	15.00
10	71.00	71.00	460.00	6.48	0	7.00	16.00
11	61.00	61.00	437.00	7.16	0	6.00	18.00
12	44.00	44.00	161.00	3.66	0	3.00	10.00
TOTALS	911.00	991.00	6509.00	7.14			

Figure III.10 DFIX1 Sample Output

FIXED TIME SIGNAL DELAY COMPUTATIONS

SAGI AND CAMPBELL METHOD

LOCATION: STONY PLAIN ROAD - 149 STREET

APPROACH: NBD LANE 2

DATE AND TIME OF SURVEY: THURSDAY, JUNE 7, 1979

COMMENTS: DACT1 TEST

NUMBER OF CYCLES PER INTERVAL: 6

DISCHARGE PER MOVEMENT FOR EACH INTERVAL

INTERVAL	THROUGH
1	75.00
2	93.00
TOTALS:	168.00

LONG DELAYS, DEMAND AND DISCHARGE FOR EACH INTERVAL

INTERVAL	DISCHARGE (PER INTERVAL)	DEMAND	TOTAL DELAY (VEH/SEC)	AVG. DELAY (SEC)	LOADED CYCLES	MAX. QUEUE	MAX. PER CYCLE DISCHARGE	END TIME (MINUTES)	AVG. CYCLE (SEC)	AVG. GREEN (SEC)
1	75.00	75.00	2887.58	38.50	1	18.00	18.00	11.40	114.00	43.17
2	93.00	99.00	2935.83	28.65	1	18.00	19.00	23.22	118.17	46.83
TOTALS:	168.00	174.00	5823.41	33.47						

Figure III.11 DACT1 Sample Output

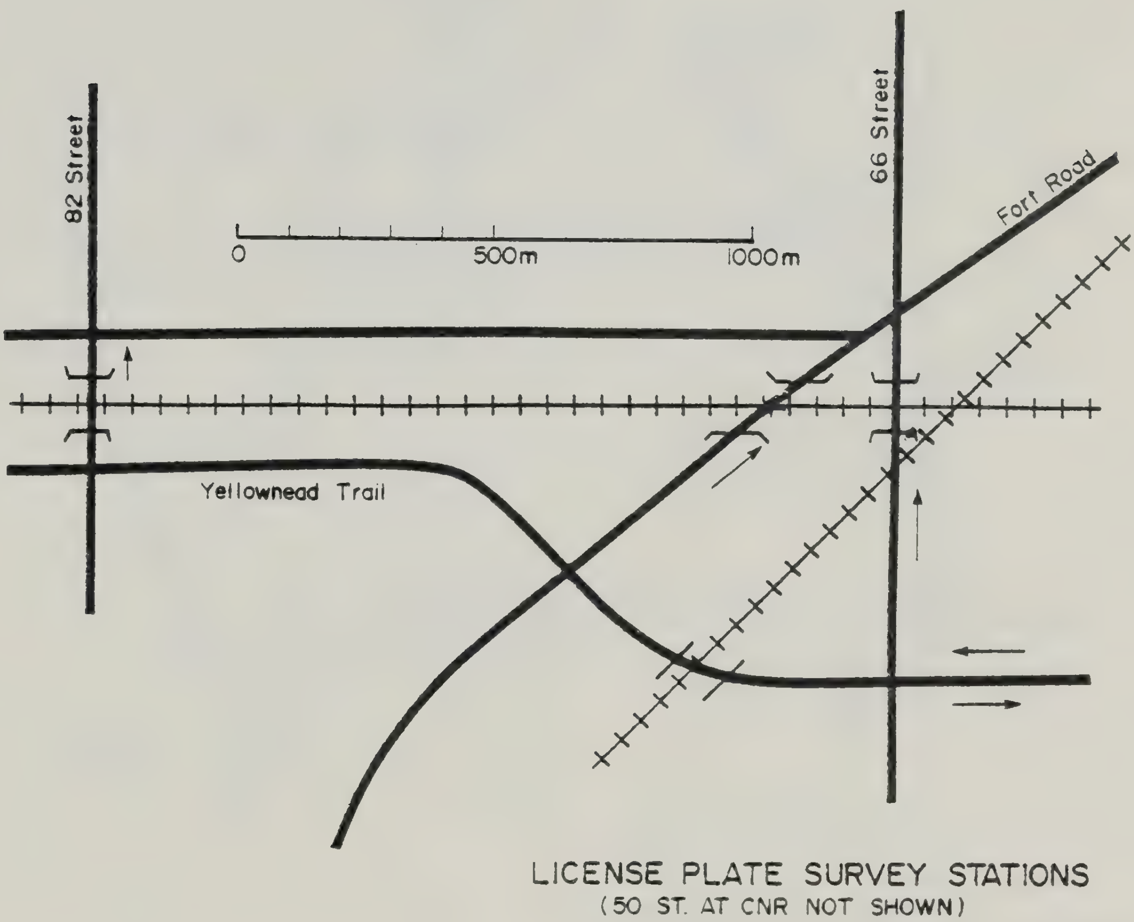


Figure III.12 License Plate Survey Stations - Fort Road and 66 Street

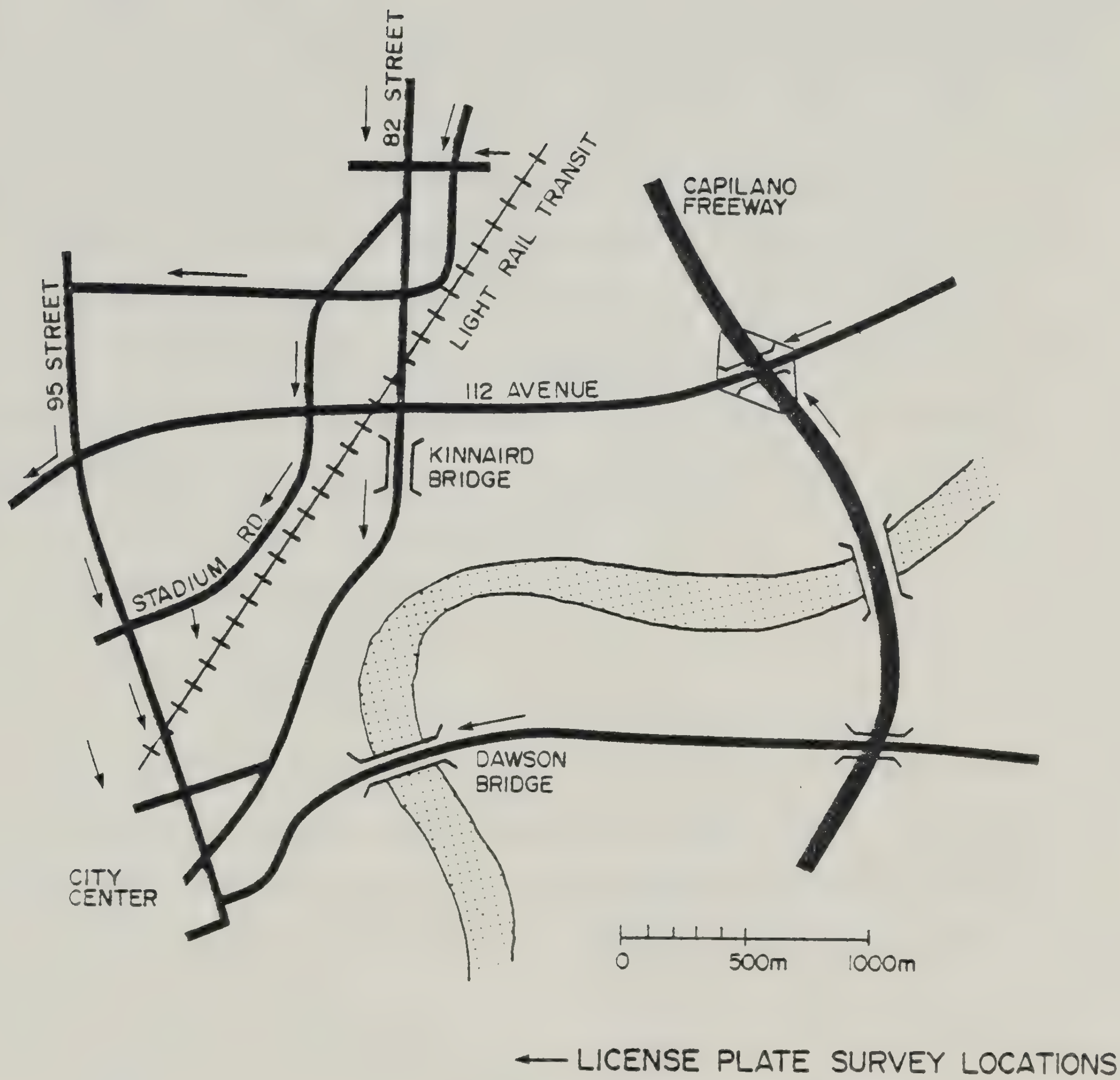


Figure III.13 License Plate Survey Stations - Kinnaird Bridge

the following information is provided:

a. number of vehicles passing the station

b. number of vehicles entering and leaving the route since the previous station

c. number of vehicles who came along the route from the previous station

d. number of vehicles who have followed the route from the initial station

'Before' and 'After' Comparison - Programs PLPBA and PLPBAN

Programs PLPBA and PLPBAN were used to compare 'before' and 'after' data for flows along the same route. As with the previous two programs, PLPBA is used for exact matches, while PLPBAN allows the user to specify the number of characters that will be accepted as an exact match. Program input is provided as follows, for two routes, A and B:

a. data for first station on route A

b. data for first station on route B

c. data for second station on route A

d. data for second station on route B

This is continued, until data for all stations has been entered. The program initially produces the same results as program PLPSN for route A, and then repeats the process for route B. In addition, flows on routes A and B are then compared to provide the following additional outputs for each station along the route:

a. number of vehicles passing both stations

b. number that passed the station on route A, but did not pass the station on route B

c. number that passed the station on route B, but did not pass the station on route A

d. number of vehicles that came from previous station on both routes

e. number of vehicles that came from the previous station on route

A, but did not do so on route B

f. the reverse of the previous point

g. the number of vehicles that have come along both routes entirely

h. the number of vehicles that have come along route A entirely, but did not do so on route B

i. the reverse of the previous point

j. which station in each pair had the larger number of vehicles pass, and by how much

Temporal Re-assignment - Program PLPTP

While the previous two programs provided substantial information about route selection, no information about changes in the time when vehicles pass through the network was provided. Fortunately, the license plate surveys did record time at the end of each 5 minute interval. A comparison of 'before' and 'after' data at the same survey station would yield the following information about travel patterns:

a. the distribution of 'before' and 'after' vehicles at the same survey station

b. what shifting from a typical daily fluctuation has occurred

Program PLPTP enables a comparison of the distribution of 'before' and 'after' trips at the same survey station. In general, the analysis must be performed in two stages. Initially, a measurement of 'typical' daily fluctuations under the same traffic conditions must be performed (ie data on two successive days). Using the results of this data comparison as a base, a comparison of the impacts of a network change on temporal assignment can then be determined. For the use of PLPTP, the number of vehicles that constitutes an exact match must be input. Time intervals need not be in successive order for analysis to be performed. Program outputs are:

a. the distribution of 'before' and 'after' vehicle matches, relative to time of the before survey (in number of vehicles, percentage,

and graphical distribution)

b. the total number of matching vehicles in the survey period

Program PLPTP was written in ALGOL, rather than FORTRAN, as used for other programs previously discussed. This was done to enable a more efficient comparison of data.

A typical PLPTP output is shown in Figure 3.14.

All of the programs described here accept license plates with 6 characters, and a maximum of 12 license plates per line of data. All license plate analysis used in the Edmonton studies made use of a 5 character match to be equivalent to an exact match.

A typical analysis, comparing 3000 license plates on a two station route, using PLPSN would require between 20 and 25 seconds of computer time with the University of Alberta Amdahl 470 V-8 computer. Costs increase linearly with the number of vehicles and the number of survey stations. Slightly higher costs would result with the use of PLPBAN or PLPTP.

DAILY FLUCTUATION

5 OR MORE CHARACTERS CONSTITUTES A UNIT MATCH

1655 PASSED 82 STREET JULY 28/81 AND 1624 PASSED 82 STREET JULY 30/81

A TOTAL OF 730 MATCHED

LISTING FOR EACH TIME: THE NUMBER AND PROPORTION THAT MATCHED FOR EACH TIME

82 ST. JULY 28/81	82 ST JULY 30/81	NUMBER MATCHED	PROPORTION MATCHED
650			
	650	6	0.38
	655	4	0.25
	700	3	0.19
	705	1	0.06
	710	0	0.00
	715	0	0.00
	720	0	0.00
	725	0	0.00
	730	0	0.00
	735	1	0.06
	740	0	0.00
	745	0	0.00
	750	1	0.06
	755	0	0.00
	800	0	0.00
	805	0	0.00
	810	0	0.00
	815	0	0.00
	820	0	0.00
	825	0	0.00
	830	0	0.00
	835	0	0.00
	840	0	0.00
	845	0	0.00
655			
	650	5	0.38
	655	4	0.31
	700	2	0.15
	705	1	0.08
	710	0	0.00
	715	0	0.00
	720	1	0.08
	725	0	0.00
	730	0	0.00

Figure III.14 Program PLPTP – Typical Output

IV. RESULTS OF THE EDMONTON STUDIES

A. Overview

This chapter presents the results of the Edmonton surveys for each study area. Procedures that were used here have been described in Chapter III. The analysis of results is presented in two stages. Initially, measured changes in network state and traffic equilibrium, consisting of results of intersection studies, are presented. Secondly, individual travel behaviour changes are discussed using the results from the license plate survey analysis.

B. Network States and Traffic Equilibrium

In each study area, the analysis of network state and traffic equilibrium focussed on a 'key intersection approach'. The incentive for traffic re-assignment in a network is a change in relative travel time between routes in the network. Each volume increase is then reflected by a volume decrease on some other route in the network (or in another time interval or mode). This assumes that equivalent transportation demand exists in the 'before' and 'after' comparison.

In the intersection studies, equilibrium changes were monitored at two locations; the key intersection approach and the key intersection approach of the primary alternate route. The primary alternate route represented a route which intuitively was expected to show the greatest flow impact due to a capacity or delay change on the critical intersection approach.

Characteristics examined in each study area are the development of new equilibrium (volume and peaking changes), along with 'before' and 'after' comparisons of delays, queues and peaking characteristics. These values will be compared for the key intersection approach and the main alternate route. In the case of Kinnaird Bridge, travel time comparisons for alternative routes through the network were also determined.

a Fort Road - 66 Street

Following the revision of intersection phasing and timings at this signal, an immediate improvement in traffic flows and operating characteristics was

noted. On the first day of the control change, northbound congestion was alleviated, but long queues existed for eastbound left turns from Fort Road to 66 Street. As a result, a timing change had to be made prior to the second afternoon peak period. This timing change lengthened the eastbound left turn phase, and relieved the queueing observed for this movement. Further minor timing changes were made one month after the control change was implemented.

'After' surveys conducted in September, 1979, indicated that northbound volumes across the CNR cordon (50 Street to 82 Street) between 16:00 to 17:50, increased slightly from 7246 to 7260 vehicles. The difference in total flows between the 'before' and 'after' data is sufficiently small that no net volume change was considered to have occured. The same 'before' and 'after' comparison showed no change in volumes northbound on either 82 Street or 50 Street, implying that the Fort Road - 66 Street intersection was the focus of most changes. The west and south approaches of Fort Road - 66 Street were therefore used as the basis for evaluating network state and traffic equilibrium changes.

Figures 4.1 and 4.2 show the development of a new equilibrium for the south and west approaches to Fort Road and 66 Street. As had been expected, a gradual increase in south approach volumes was observed, with a slight decrease in west approach volumes also being noted. Comparing Figures 4.1 and 4.2, some oscillation in flows is apparent. This behaviour might be attributed to vehicles trying different routes on different days in a search for the shortest route through the network. Stabilization in approach volumes was apparent after a 2 week period.

'Before' and 'after' delays and queueing are compared for the south and west approaches in Figures 4.3 through 4.6. Little change in either queues or delays occured on the west approach. Conversely, a major improvement was observed on the south approach. On the south approach, delay reductions were over 4 minutes per vehicle, and queue lengths declined by 40 vehicles per lane, over the entire peak period.

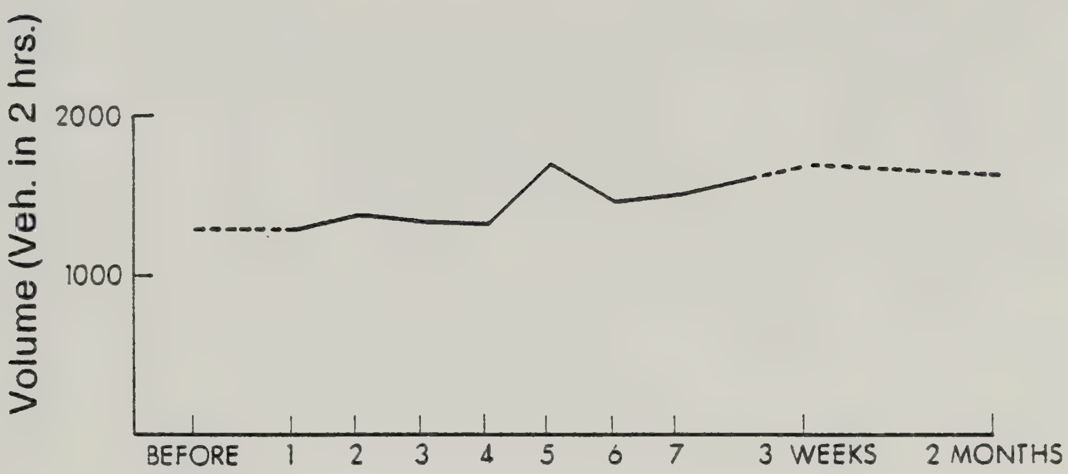


Figure IV.1 Development of Traffic Equilibrium - South Approach - Fort Road and 66 Street

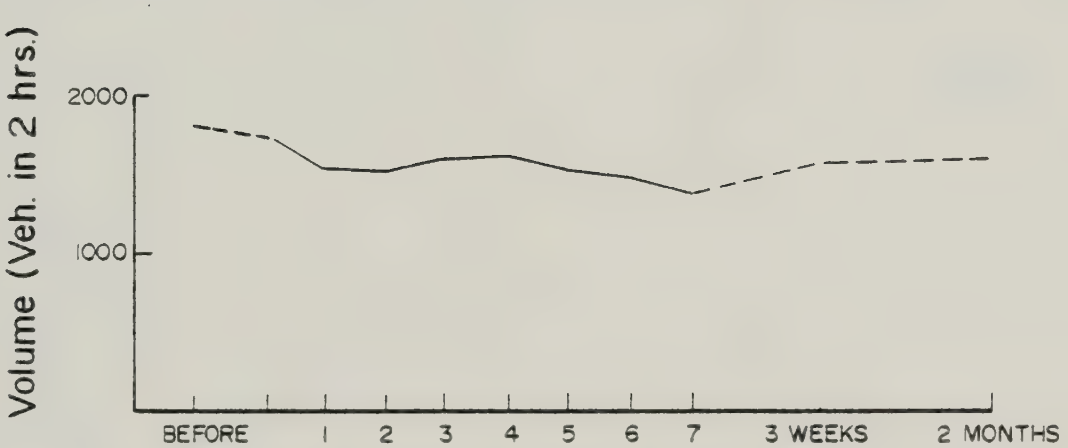


Figure IV.2 Development of Traffic Equilibrium - West Approach - Fort Road and 66 Street

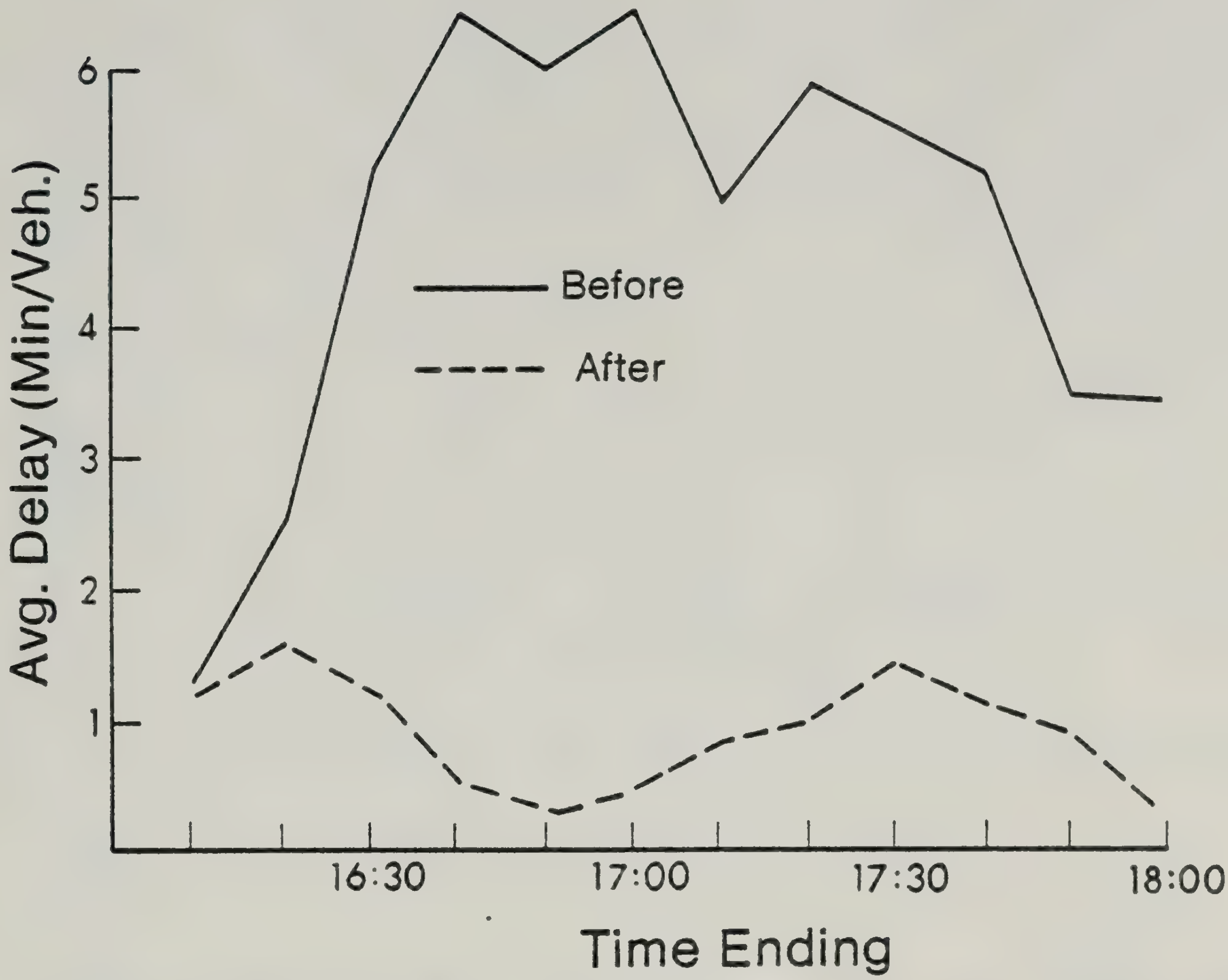


Figure IV.3 Vehicular Delays - South Approach - Fort Road and 66 Street

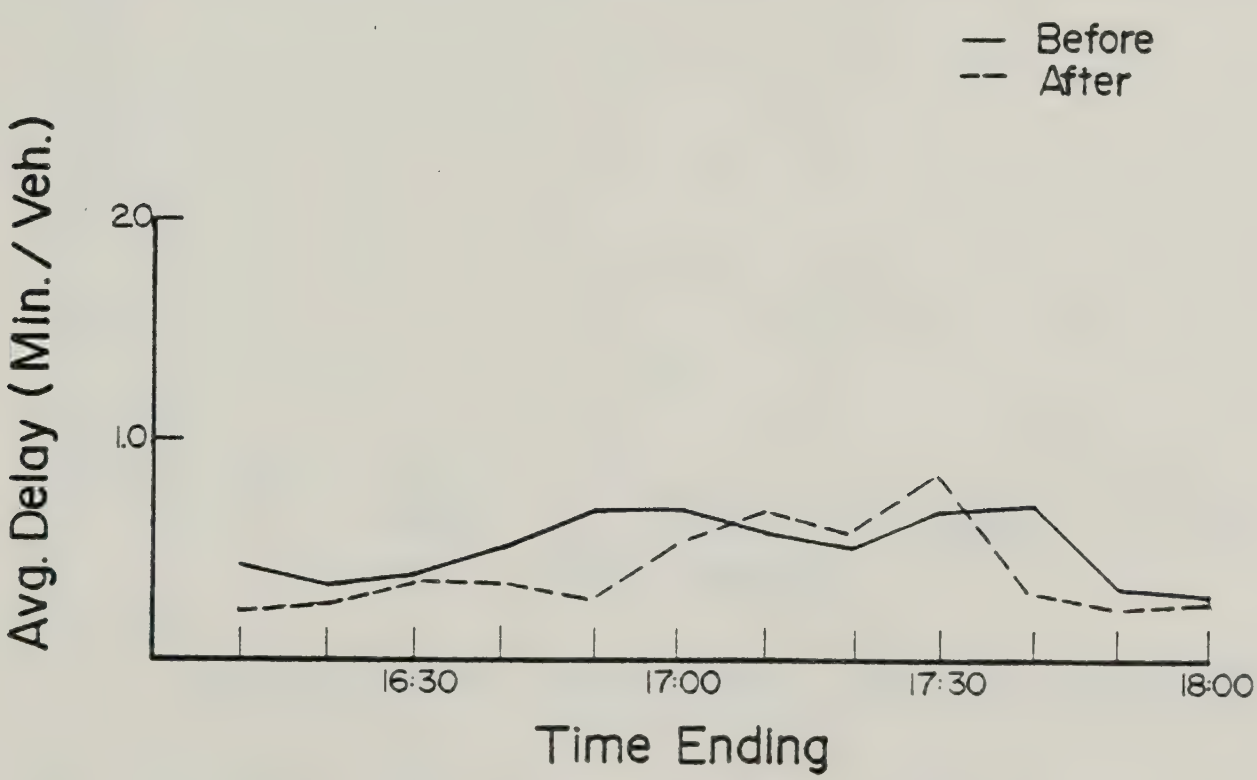


Figure IV.4 Vehicular Delays - West Approach - Fort Road and 66 Street

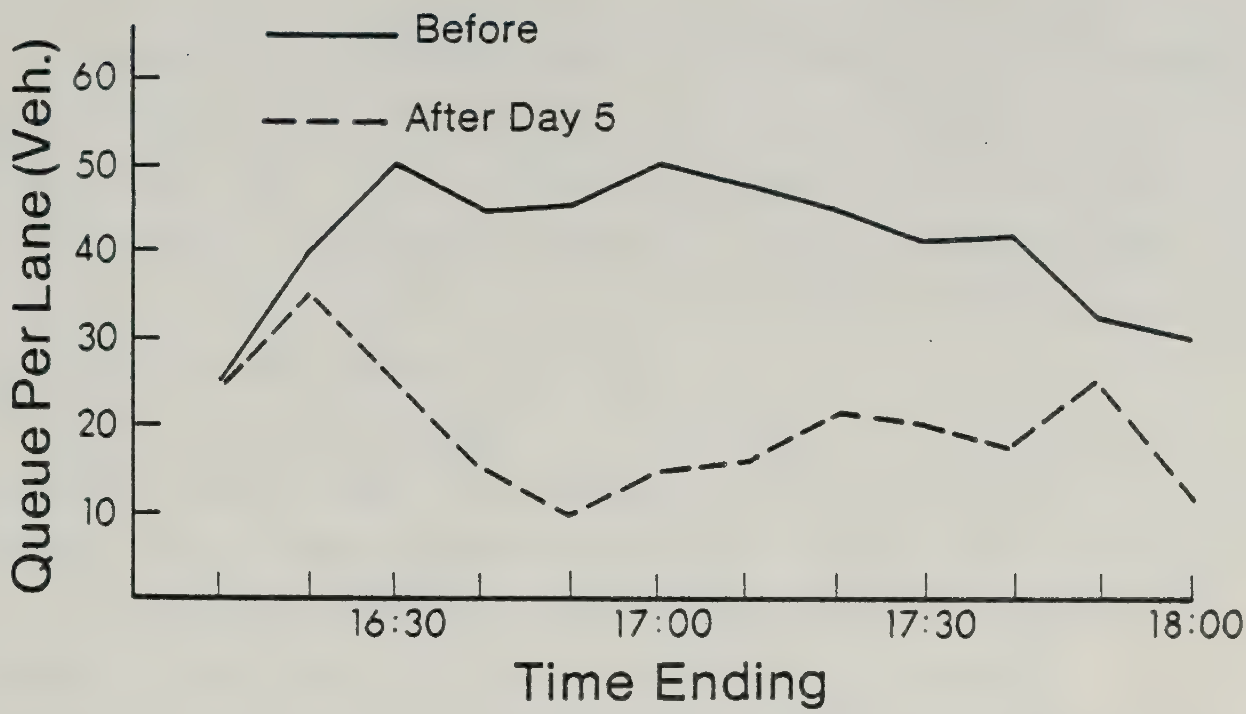


Figure IV.5 Queueing - South Approach - Fort Road and 66 Street

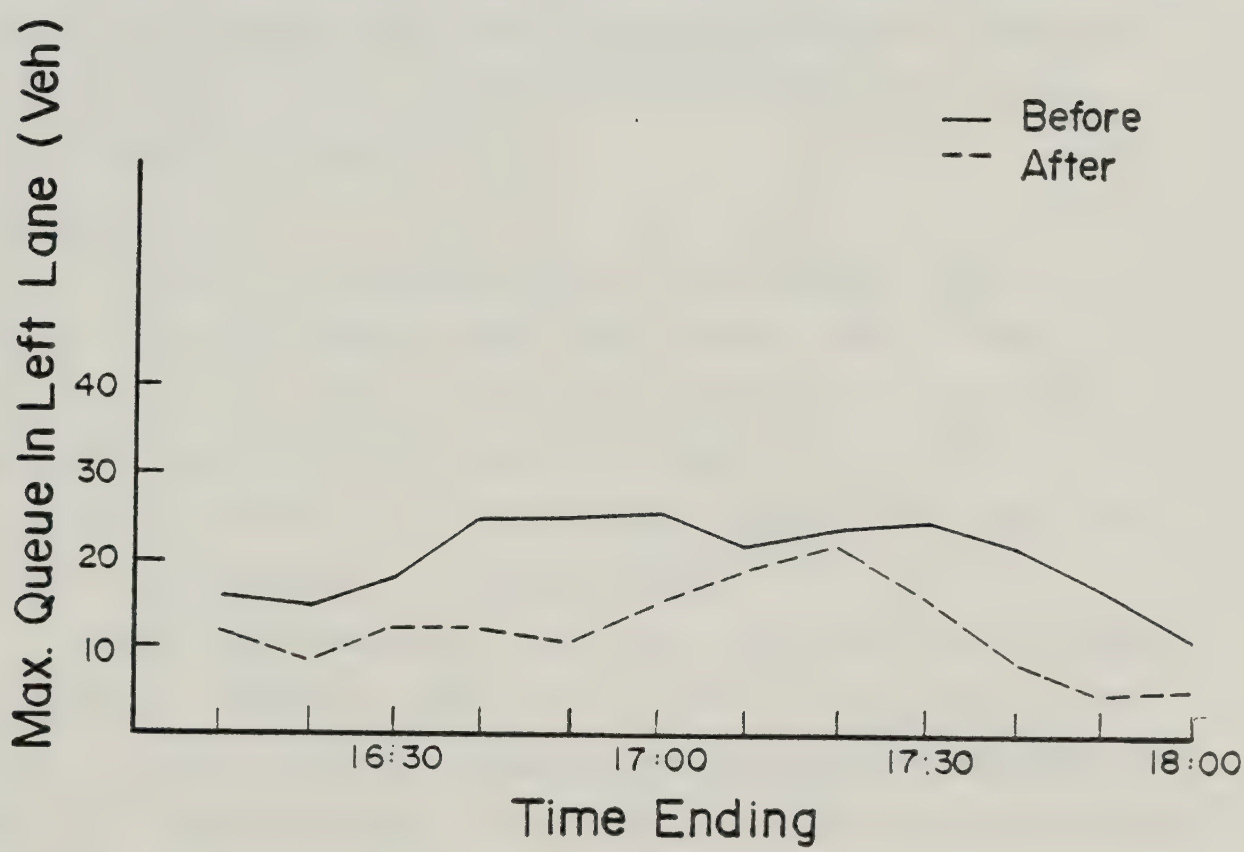


Figure IV.6 Queueing - West Approach - Fort Road and 66 Street

Examining the peaking characteristics for the west and south approaches, shown in Figures 4.7 and 4.8, a sharper peak appears to exist at both locations in the 'after' case. The percentage of demand within the peak hour for the south approach to Fort Road - 66 Street is shown in Table 4.3. These results show a large fluctuation in the proportion of flows within the peak, with no definite trend apparent.

The long term flow changes at this intersection are also of some interest. An intersection count was conducted at Fort Road - 66 Street in October, 1980. This count revealed that peak period (16:00 - 18:00) volumes on the west and south approaches, combined, had increased by 5% from the September, 1979 values (from 3533 to 3712 vehicles). The peaking characteristics at Fort Road and 66 Street have maintained the sharper profile established after July, 1979. No major delay increases have occurred since the intersection improvements were made. This may also reflect the construction of a northbound right turn bay in the fall of 1979, which increased south approach capacity by about 20%.

b Kinnaird Bridge

The analysis of the Kinnaird area was more complex, due to a large study area with many alternate routes being available. A factor present in this area, which was not common to the other study areas, was the complete closure of a major link in the network. The presence of a total closure forced all drivers that used this link to select alternate routes, a result which would not have occurred with only a partial link closure.

To ensure that 'before' and 'after' results were comparable, all signal timing changes made for the detour were in place for one week or more before the actual closure began (with the exception of signals immediately adjacent to the bridge). Surveys at these signalized intersections were conducted 'before' and 'after' these timing changes, in order that flow changes caused by signal timing changes could be distinguished from flow changes caused by the detour. These counts indicated that signal timing changes alone did not cause flow variations outside the normal daily traffic fluctuation.

Table IV.1 Peaking - S. Approach - Fort Road & 66 Street

Date	Volume 1600 - 1800	Volume 1610 - 1710	Percent in Peak Hour
April 19	1281	636	49.6
July 10	1260	669	53.0
July 11 (Day 1)	1330	744	55.9
Day 2	1402	765	54.6
Day 3	1352	710	52.5
Day 4	1238	652	52.7
Day 5	1708	855	50.0
Day 6	1431	793	55.4
Day 7	1481	828	55.9
August 2	1676	886	52.9
Sept. 20	1594	847	53.1

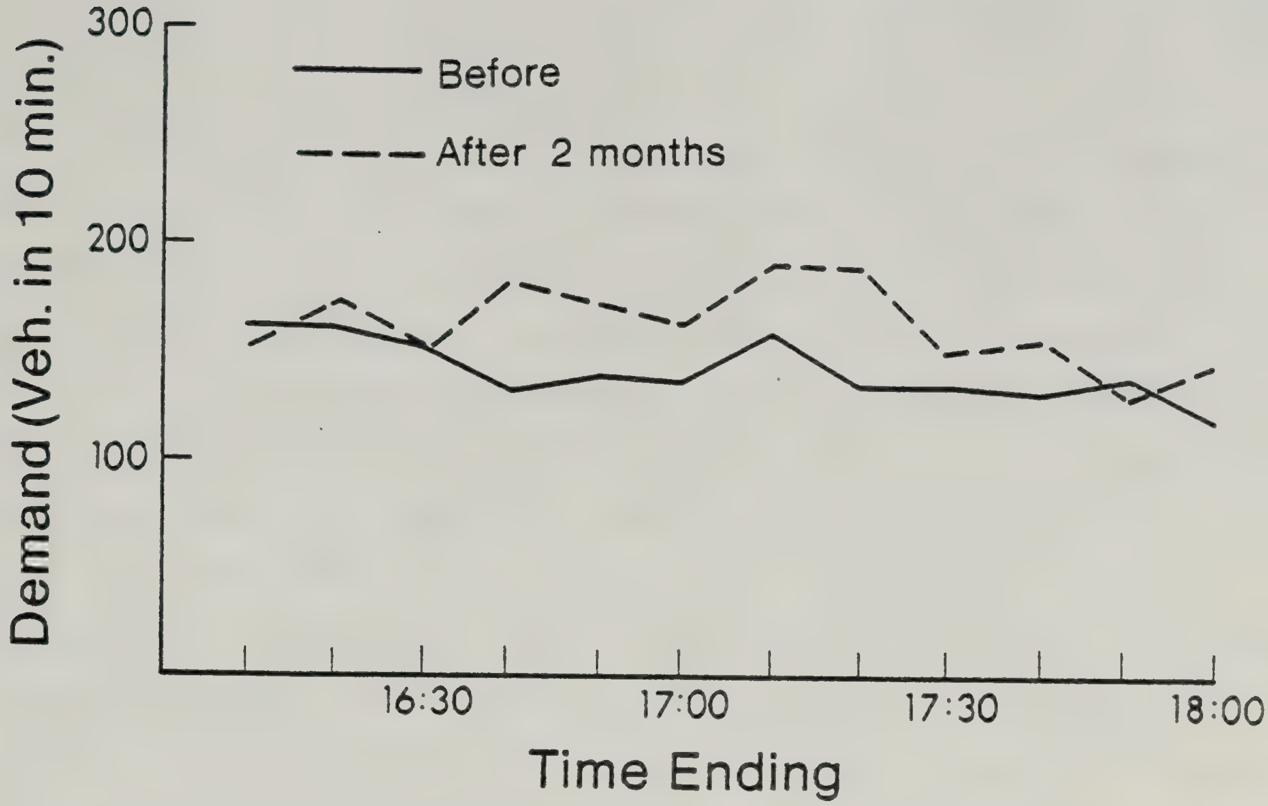


Figure IV.7 Peaking Characteristics – South Approach – Fort Road and 66 Street

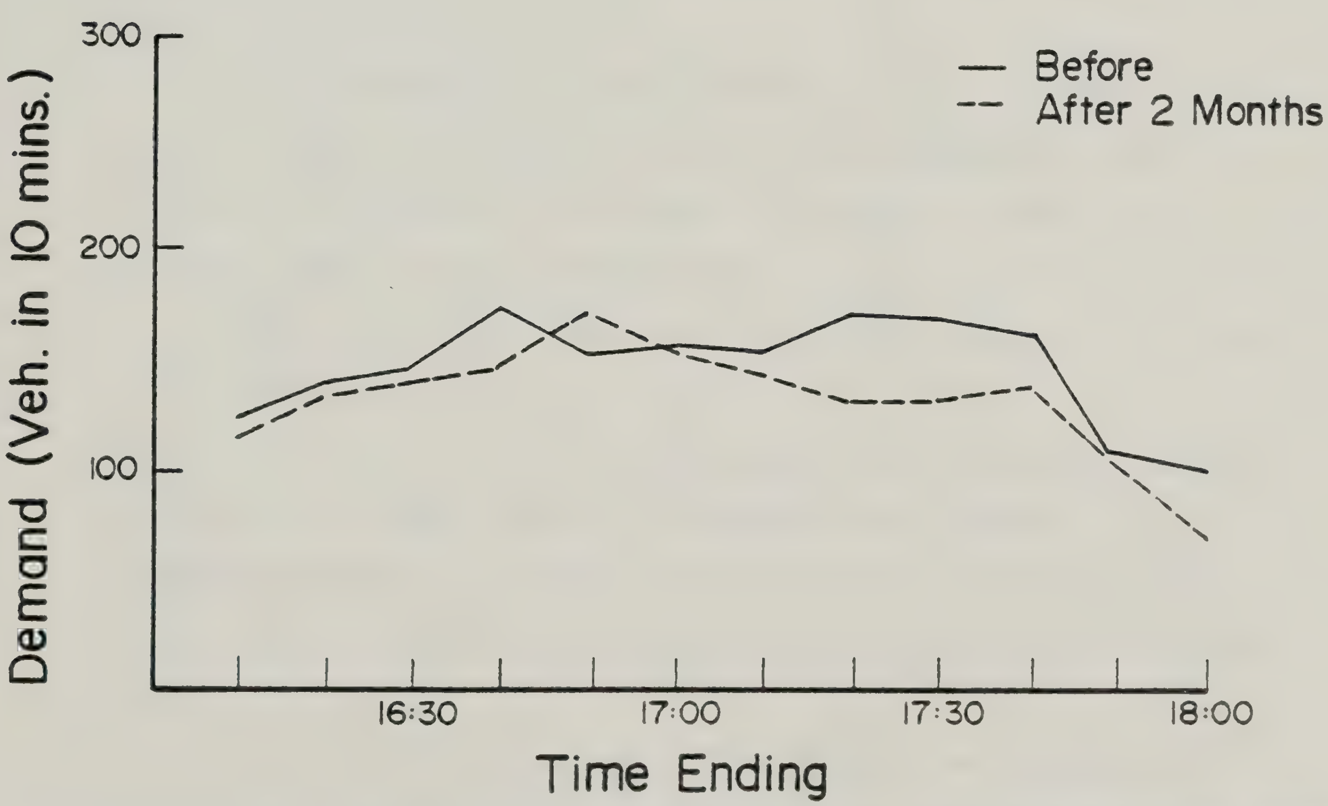


Figure IV.8 Peaking Characteristics – West Approach – Fort Road and 66 Street

A comparison of 'before' and 'after' flows from the northeast revealed that volumes between 7:00 and 9:00 declined from 7301 to 6373, a 13% decrease. Almost all of this decrease consisted of flows originating from the north. Up to 400 vehicles of this decrease could consist of 'shortcutting' traffic, which was not recorded. The remaining difference was attributed to shifts of flows outside the study area, most likely to 97 Street or to 118 Avenue. No adjustment factors were applied to volumes in the study area.

Two major flow patterns were impacted by the closure of Kinnaird Bridge; flows from the east to the CBD and flows from the north to the CBD. Figure 4.9 illustrates alternate routes available for these flows. For flows from the north, the key intersection approach was the north approach to 112 Avenue – 86 Street, while the key approach for flows from the east was at 112 Avenue and 82 Street. Flow changes on the north approaches to both 112 Avenue – 86 Street and 111 Avenue – 95 Street were monitored to determine volume shifts. For flows from the east, the locations compared were the east approaches to 112 Avenue – 82 Street and 106 Avenue – 84 Street.

Flows from the North

The development of volume equilibrium for the AM peak period is shown in Figures 4.10 and 4.11 for the north approaches to both 112 Avenue – 86 Street and 111 Avenue – 95 Street. Volumes at both locations appear to have stabilized within 4 days of the Kinnaird closure.

Table 4.2 indicates travel times for alternate routes from the north to the CBD.

These travel times assumed free flow travel at the speed limit, between intersections. At signals, delays were calculated using SINTRAL, for undersaturated signals, and DFIX1 for oversaturated intersections. Signal delays were then added to link travel times to obtain total route travel time.

Travel times are shown to initially increase, then decrease after traffic flows had stabilized. Travel times from the north, after network stabilization, were close to one minute longer than those that had

Table IV.2 Travel Times from North to the CBD

Route	Before (min)	Day 1 After (min)	Day 7 After (min)
1	7.2	7.4	7.5
2	5.8	10.2	7.0
3	6.0	n/a	n/a

Figure IV.9 Alternate Network Routes for Travel Time Comparison in Kinnaird Area

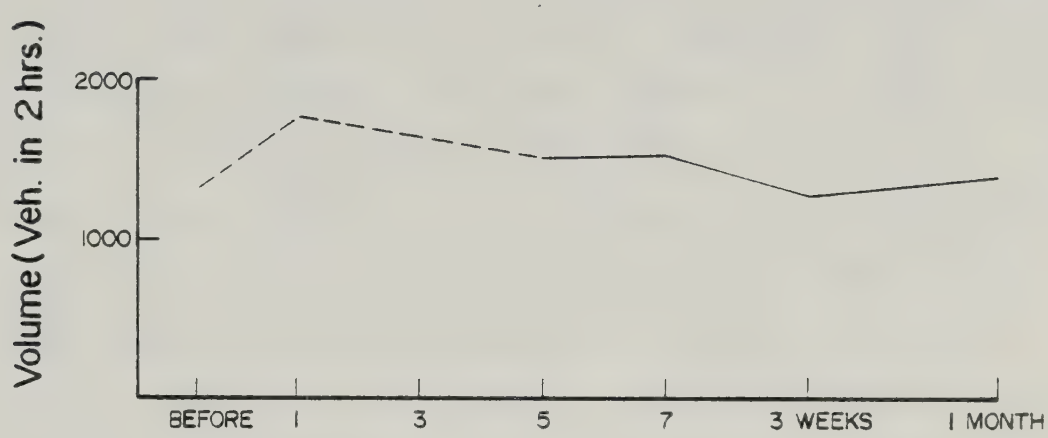


Figure IV.10 Development of Traffic Equilibrium - North Approach - 112 Avenue and 86 Street

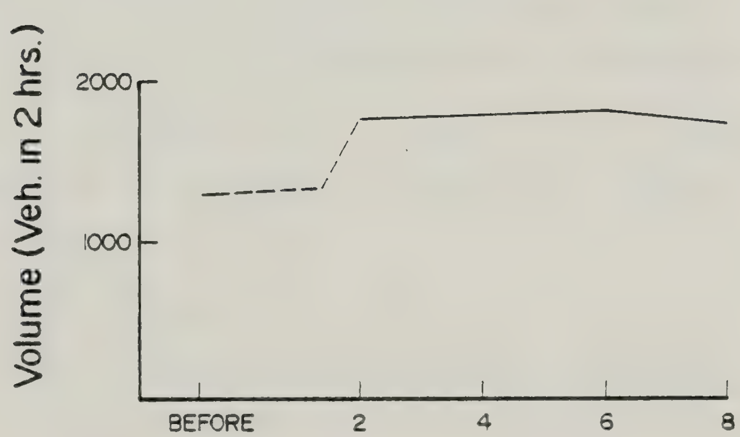


Figure IV.11 Development of Traffic Equilibrium - North Approach - 111 Avenue and 95 Street

previously existed.

Delay and queue comparisons, 'before' and 'after', for the north approach to 112 Avenue - 86 Street (Figures 4.12 and 4.13) indicate an increase in both delays and queues from values that existed prior to the Kinnaird closure. Comparisons for 111 Avenue - 95 Street are not provided, as saturated conditions were never reached in the 'after' case at this signal (ie no significant increase in either delays or queues).

Peaking characteristics are shown in Figures 4.14 and 4.15 for the north approaches to 111 Avenue - 95 Street and 112 Avenue - 86 Street. 'After' conditions show little change in the shape of the peak at 111 Avenue - 95 Street. At 112 Avenue - 86 Street, however, the peak has flattened in the after situation, but total volumes have increased from pre-closure levels.

The variation with time of the proportion of flow within the peak hour at 112 Avenue - 86 Street and 111 Avenue - 95 Street are shown in Tables 4.3 and 4.4. These results indicate that little change in the peak proportion of flows occurred at 111 Avenue - 95 Street. At 112 Avenue - 86 Street, however, a noticeable change in peaking behaviour occurs by Day 5 of the Kinnaird detour, and remains even after the removal of barricades on 112 Avenue. This may suggest temporal re-assignment, or the shifting of peak hour traffic to some other route (ie 'shortcutting').

Flows from the East

Traffic volume changes over time are shown in Figures 4.16 and 4.17 for the east approaches to 112 Avenue - 82 Street and 106 Avenue - 84 Street. At 112 Avenue - 82 Street, a major control change was made 3 weeks after the start of the detour. This change removed the barricades in the left lane of 112 Avenue, east of 82 Street, resulting in an additional traffic lane through the signal at 112 Avenue - 82 Street. This change in strategy was not planned, but had to be made in response to numerous public complaints about excessive delays along 112 Avenue.

Table IV.3 Peaking - N. Approach - 112 Avenue & 86 Street

Date	Volume 0700 - 0900	Volume 0715 - 0815	Percent in Peak Hour
April 11	1291	762	59.0
May 1 (Day 1)	1794	1055	58.8
Day 3		721	
Day 5	1524	795	52.2
Day 7	1557	792	50.9
May 16	1271	682	53.7
May 25	1431	724	50.6

Table IV.4 Peaking- N. Approach - 111 Avenue & 95 Street

Date	Volume 0700 - 0900	Volume 0715 - 0815	Percent in Peak Hour
April 5	1271	795	62.5
May 2 (Day 2)	1786	1113	62.3
Day 4	1791	1133	63.3
Day 6	1843	1173	63.6
Day 8	1755	1100	62.7

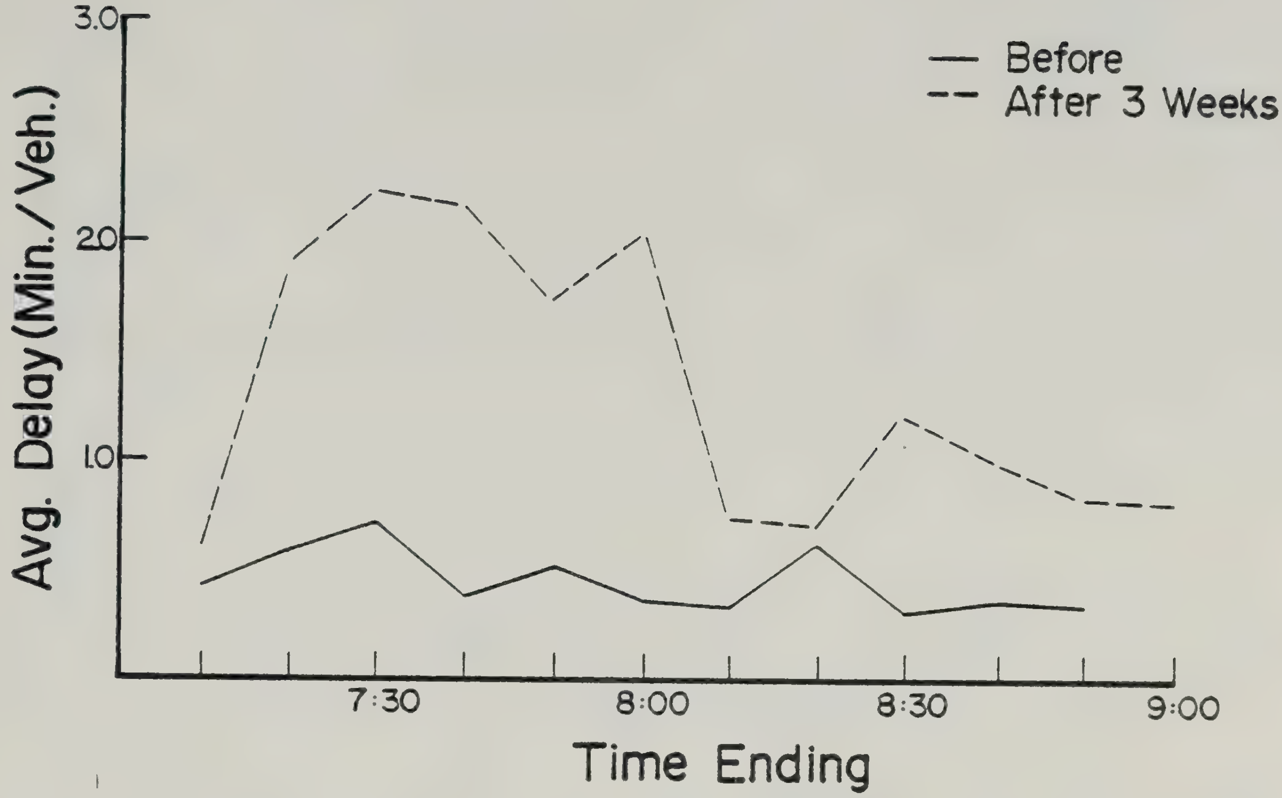


Figure IV.12 Vehicular Delays - North Approach - 112 Avenue and 86 Street

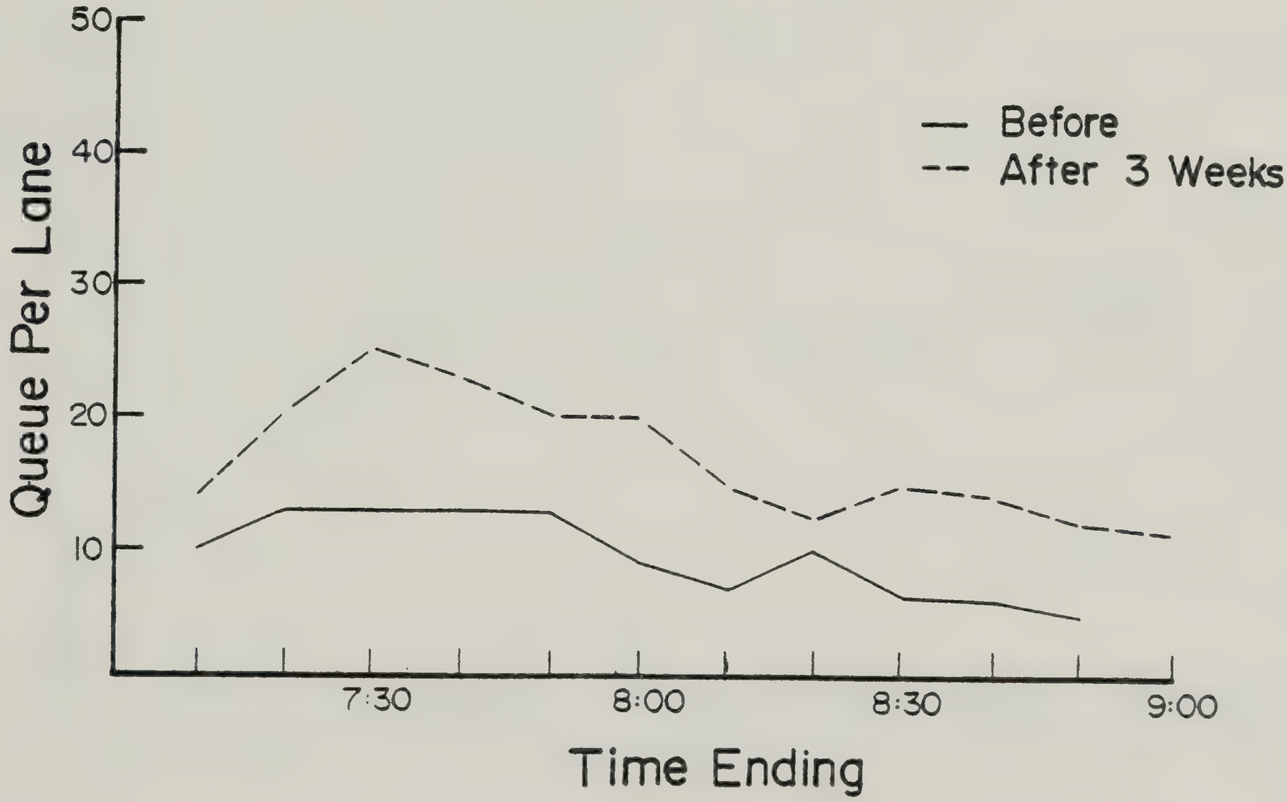


Figure IV.13 Queueing - North Approach - 112 Avenue and 86 Street

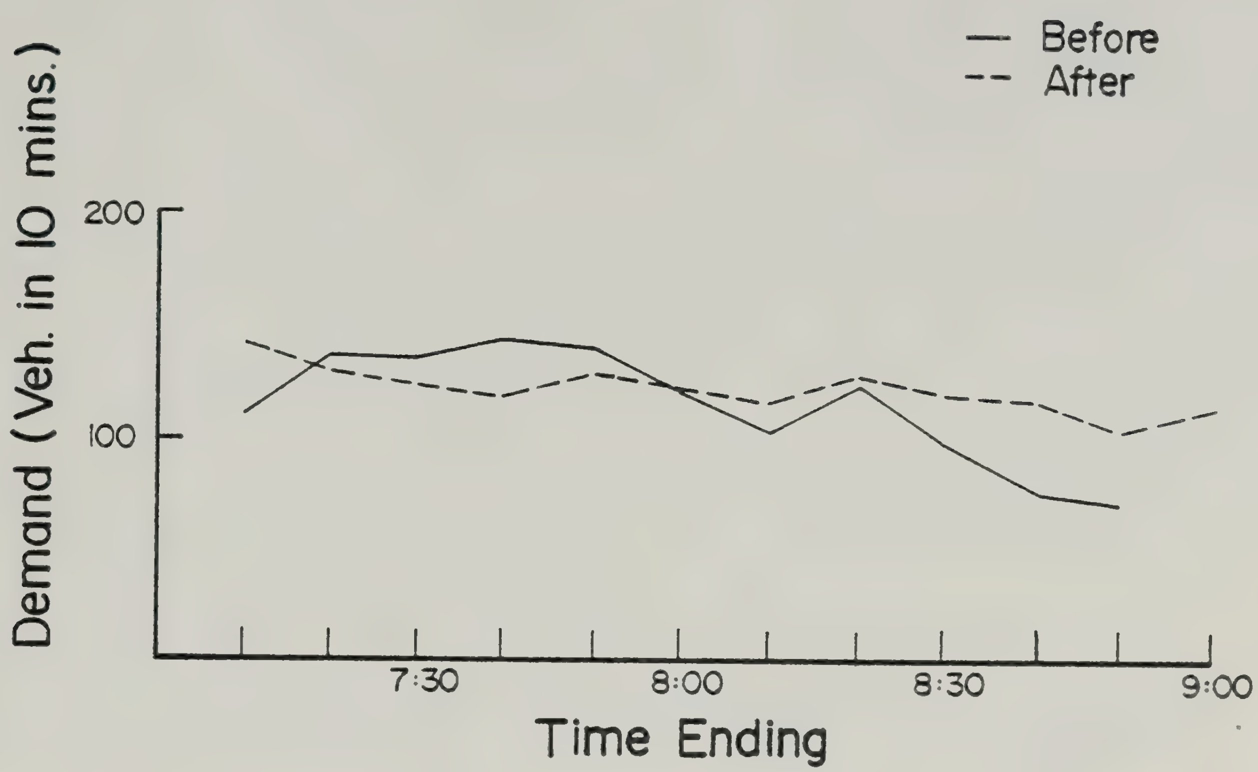


Figure IV.14 Peaking Characteristics - North Approach - 112 Avenue and 86 Street

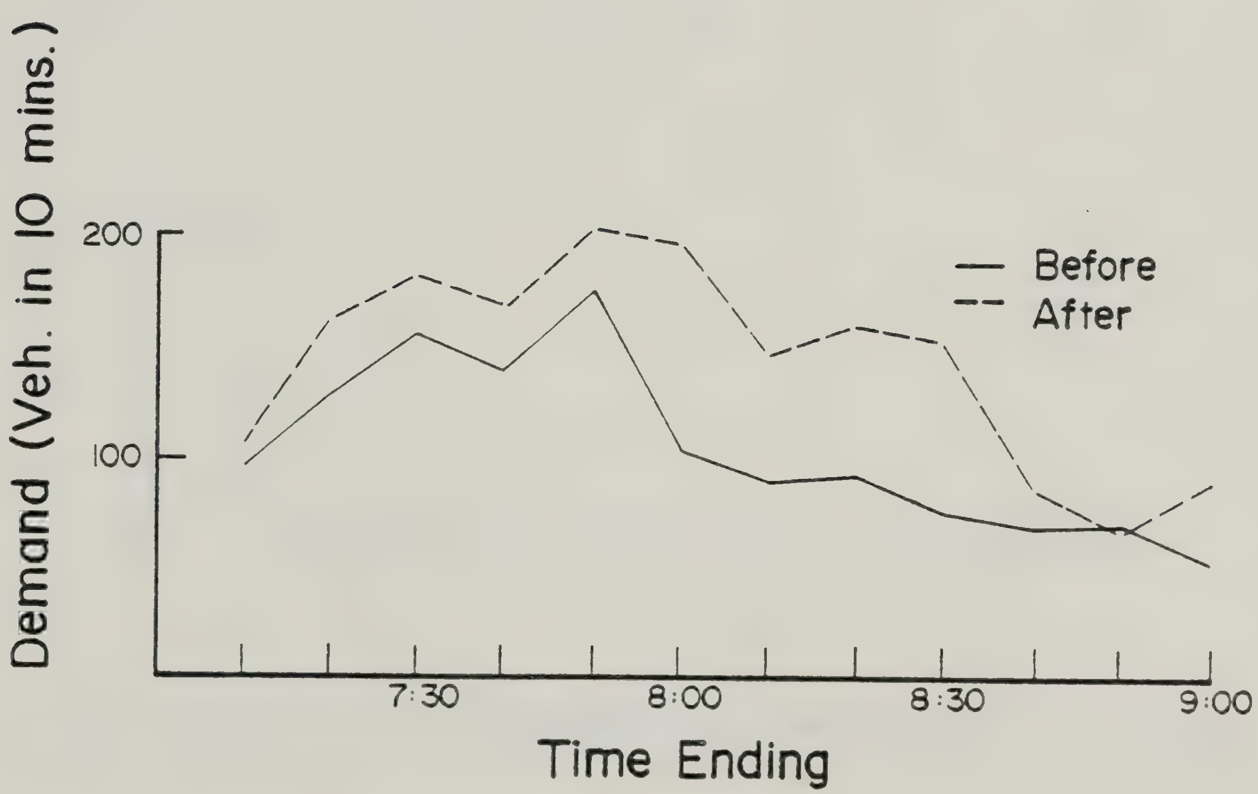


Figure IV.15 Peaking Characteristics - North Approach - 111 Avenue and 95 Street

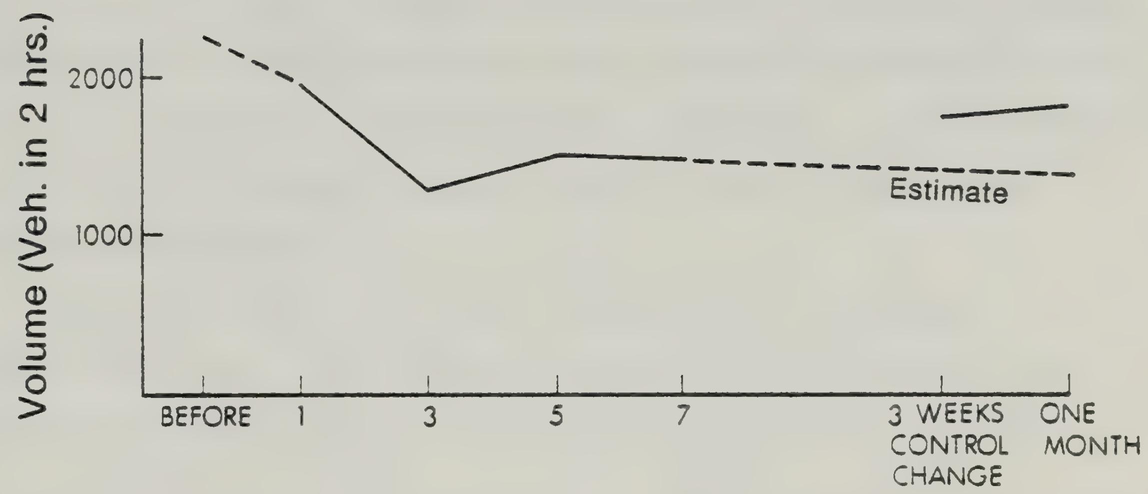


Figure IV.16 Development of Traffic Equilibrium - East Approach - 112 Avenue and 82 Street

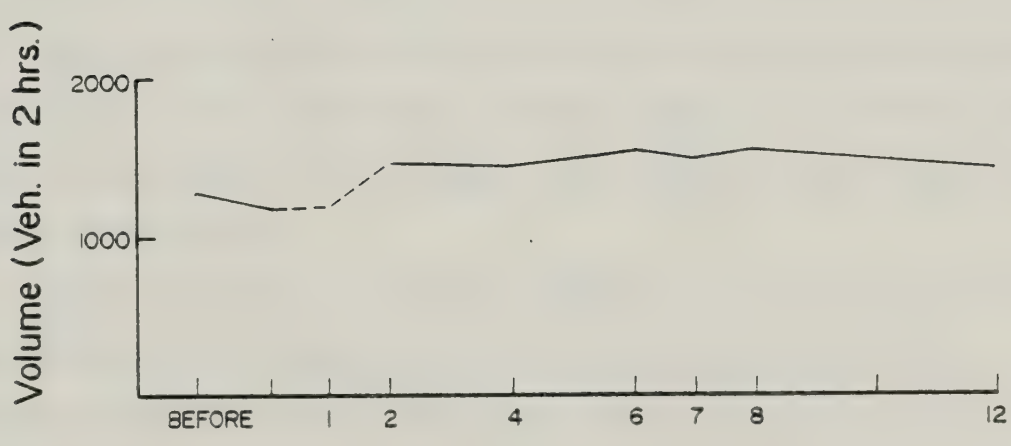


Figure IV.17 Development of Traffic Equilibrium - East Approach - 106 Avenue and 84 Street

Volumes on 112 Avenue increased after this control change was made. As a result, it is uncertain whether traffic flows from the east had reached an equilibrium level prior to the removal of the 112 Avenue barricades. Figure 4.16 appears to indicate that volume stability was re-established within 4 to 6 days after the detour commenced. The continuation of public complaints about excessive delays even after the first two weeks of the closure provides evidence that complete flow stabilization had not occurred. It appears that an 'unstable equilibrium state' had been reached within the first week of the detour.

Table 4.5 presents travel times from the east to downtown via alternate routes. After 7 days, travel times along the 112 Avenue route had still not decreased to anywhere near the times via the Dawson Bridge route. This reluctance of drivers to use 106 Avenue may reflect a percieved additional travel time due to this route having two river crossings. It is of interest that a 'penalty' for multiple river crossings has been incorporated into many route assignment models. The data collected here suggests that a 'penalty' of up to 4 minutes could be assigned to a route involving two river crossings. It is not known whether, in the long term, travel times would have stabilized as more people became aware of the existence of the 106 Avenue / Dawson Bridge route. Following the removal of barricades on 112 Avenue, travel times on both routes from the east were reduced.

Queues and delays on the east approach to 112 Avenue - 82 Street are shown in Figures 4.18 and 4.19 for 'before' and 'after' conditions. The 'before' queues and delays are not shown prior to 7:40, as the 112 Avenue - 82 Street signal was operating in the wrong timing plan, causing abnormal queueing and delays. These figures show that a major degradation of both performance measures occurred at 112 Avenue - 82 Street after the closure. Queue lengths of up to 100 vehicles were observed in the highest volume time periods. Following the removal of barricades on 112 Avenue, queues and delays returned to levels which had

Table IV.5 Travel Times from the East to the CBD

Route	Before (min)	Day 1 After (min)	Day 7 After (min)	3 wks After (min)
4	6.5	14.6	10.3	6.4
5	5.8	n/a	n/a	n/a
6	6.4	6.5	6.5	6.5

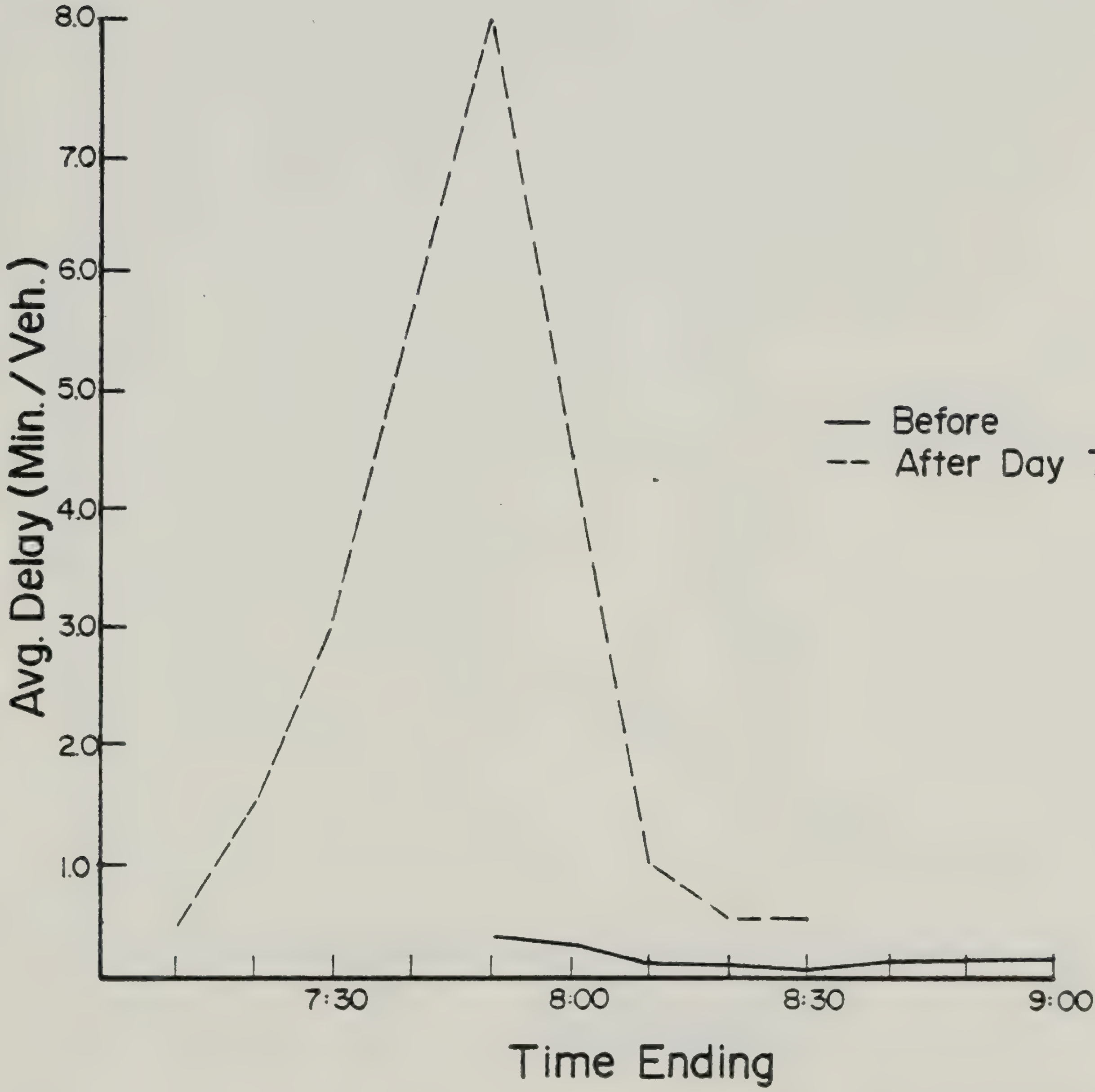


Figure IV.18 Vehicular Delays - East Approach - 112 Avenue and 82 Street

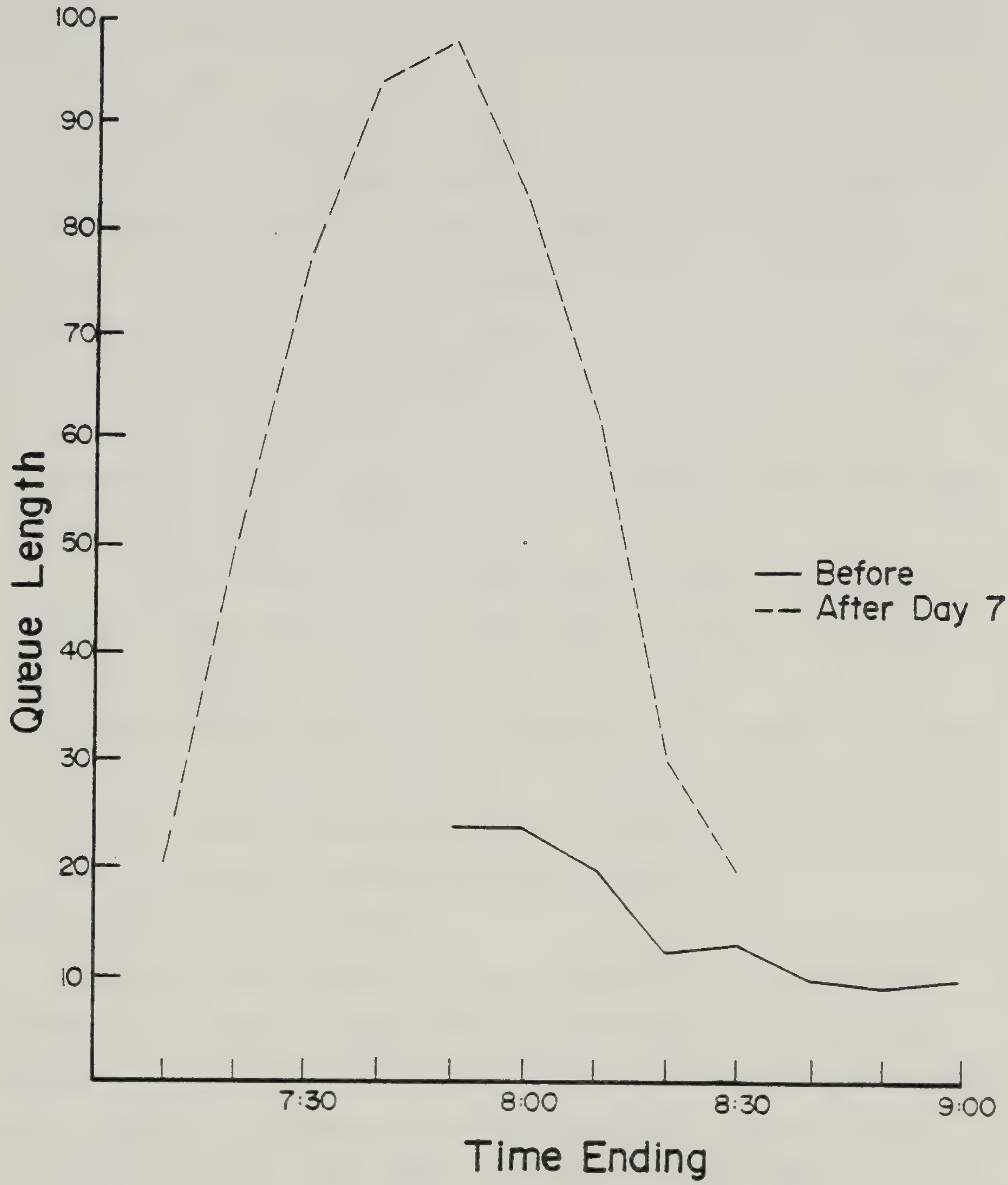


Figure IV.19 Queueing - East Approach - 112 Avenue and 82 Street

existed before the detour began.

Delays and queues on the east approach to 106 Avenue and 84 Street did not show any substantial increase as a result of increased volumes. Delays of up to one or two cycles did exist for the peak 15 minutes, with the bridge closure in place. These delays were only observed on some days.

Peaking characteristics 'before' and 'after' are compared in Figures 4.20 and 4.21 for the east approach to 106 Avenue – 84 Street and 112 Avenue – 82 Street. A substantial flattening of the peak occurred for flows along 112 Avenue. This broadening of the peak occurs to such an extent that 10 minute volumes fluctuate within a range of only 30 vehicles over the entire two hour morning peak period. On 106 Avenue, some sharpening of the peak was noted in the 'after' case. This may be attributed to a higher proportion of traffic shifting to 106 Avenue from 112 Avenue within the peak 30 minutes.

The development of new peaking characteristics, with time, are shown in Tables 4.6 and 4.7. At 106 Avenue – 84 Street, the peak appears to sharpen in the first days of the detour, but returns to pre-detour values by Day 6 of the closure. At 112 Avenue – 82 Street, a flatter peak is apparent after Day 5 of the detour. As with flows from the north, this may imply either temporal re-assignment, or a change in route selection, or a combination of these factors.

c Stony Plain Road - 142 Street

The traffic control changes at Stony Plain Road – 142 Street were performed in a number of stages. Initially, computerized traffic control was implemented at Stony Plain Road – 142 Street. The elimination of the westbound left turn phase at this location, in the AM peak period, resulted in some improvement to through traffic flows both eastbound and northbound. In the second stage, road widening was completed on Stony Plain Road between 142 Street and 139 Street. As part of this widening, the critical northbound right turn movement was changed from a single lane to a two lane movement. As

Table IV.6 Peaking – E. Approach – 112 Avenue & 82 Street

Date	Volume 0700 – 0900	Volume 0715 – 0815	Percent in Peak Hour
April 9	2233	1314	58.8
May 1 (Day 1)	1946	1149	59.0
Day 3			
Day 5	1507	878	58.3
Day 7	1483	768	51.8
May 17 (Day 12)	1734	908	52.4

Table IV.7 Peaking– E. Approach – 106 Avenue & 84 Street

Date	Volume 0700 – 0900	Volume 0715 – 0815	Percent in Peak Hour
April 6	1284	797	62.1
April 27	1185	755	63.7
May 2 (Day 2)	1484	952	64.2
Day 4	1461	966	66.1
Day 6	1544	974	63.1
Day 7	1492	952	63.8
Day 8	1540	940	61.0
May 18	1419	886	62.4

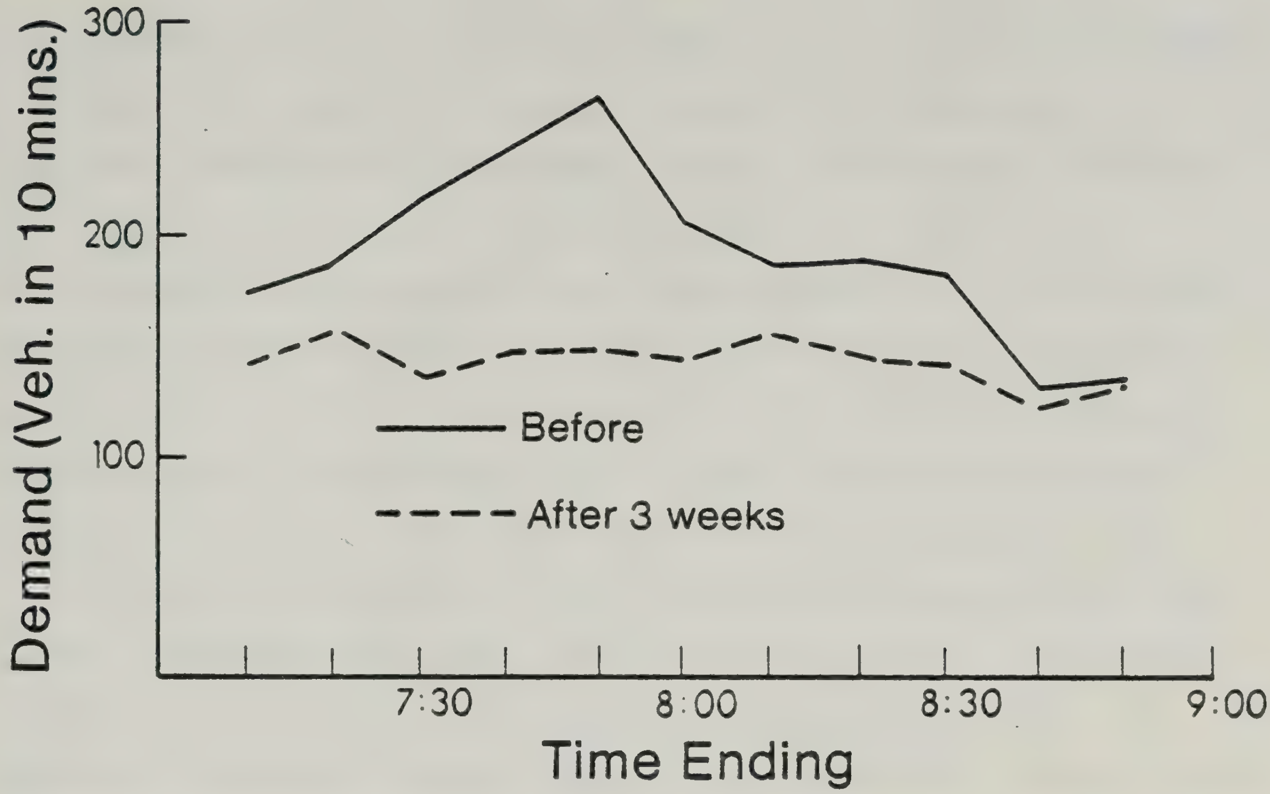


Figure IV.20 Peaking Characteristics - East Approach - 112 Avenue and 82 Street

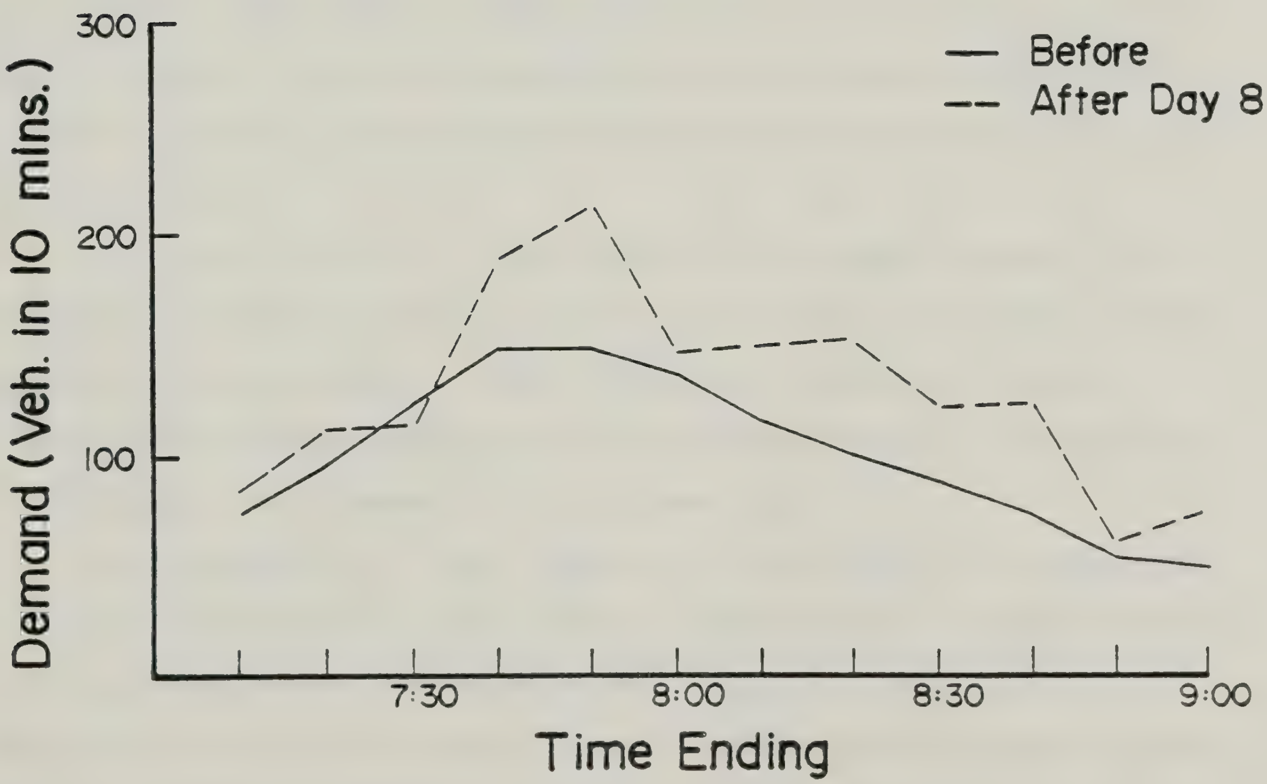


Figure IV.21 Peaking Characteristics - East Approach - 106 Avenue and 84 Street

well, an eastbound double left turn was implemented at the new signal installed at the Stony Plain Road – 102 Avenue intersection. These measures, in combination, resulted in major reductions in delays and queues for northbound right turns, as well as further improving eastbound traffic operation.

Eastbound flows across the Groat Road screenline in the AM peak period were 6500 and 6600 vehicles, 'before' and 'after'. This figure indicated that a negligible change had taken place in total flows from the west end between 'before' and 'after' data collection. Analysis of 'after' volumes showed that no shift from 102 Avenue / Stony Plain Road to either 107 Avenue or Keillor Road had occurred. In addition, no change in flows had occurred at study area boundary intersections along either 149 Street or 124 Street. It was therefore concluded that, in the short term, impacts of the Stony Plain Road – 142 Street traffic management scheme appeared to be localized. The following section discusses these local impacts.

From the south, on 142 Street, major flows exist for both through traffic and right turn movements, at the Stony Plain Road intersection. The right turn movement experienced the highest delay prior to the traffic management scheme, resulting in the through movement being an attractive alternate route. As a result, the impact to all northbound flows had to be considered in the traffic equilibrium study.

The Stony Plain Road – 142 Street area is somewhat unique, in that drivers have the ability to select alternate routes (ie through or right) with the knowledge of queue lengths on both routes. Daily fluctuations in queues (resulting from incidents, weather or traffic volumes) resulted in a large day to day fluctuation in the distribution of northbound traffic.

The development of traffic volumes for each stage in the improvement is shown in Figure 4.22 for the northbound right turn lane, and Figure 4.23 for northbound through lanes. The development of equilibrium here is not well defined. This is due to construction activity, an incident which affected roadway capacity and traffic distribution on almost a day to day basis.

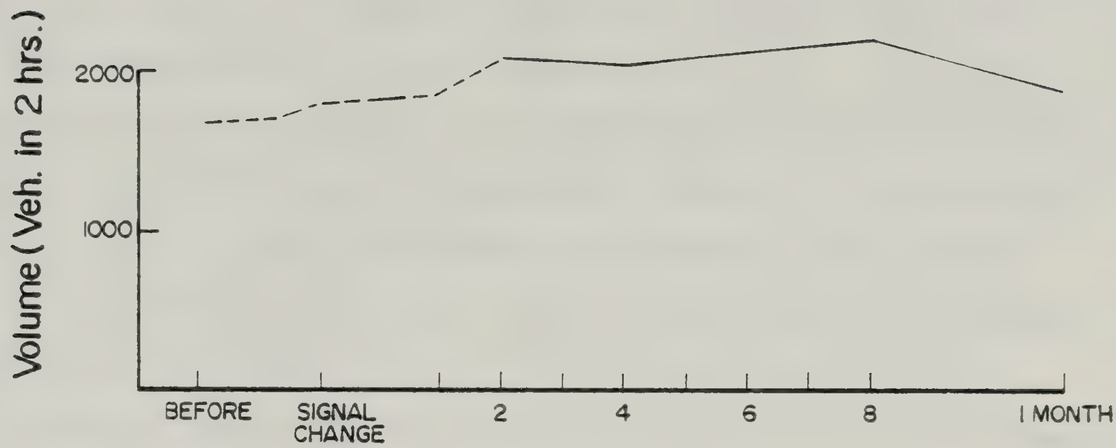


Figure IV.22 Development of Equilibrium – Northbound Right Turn – Stony Plain Road and 142 Street

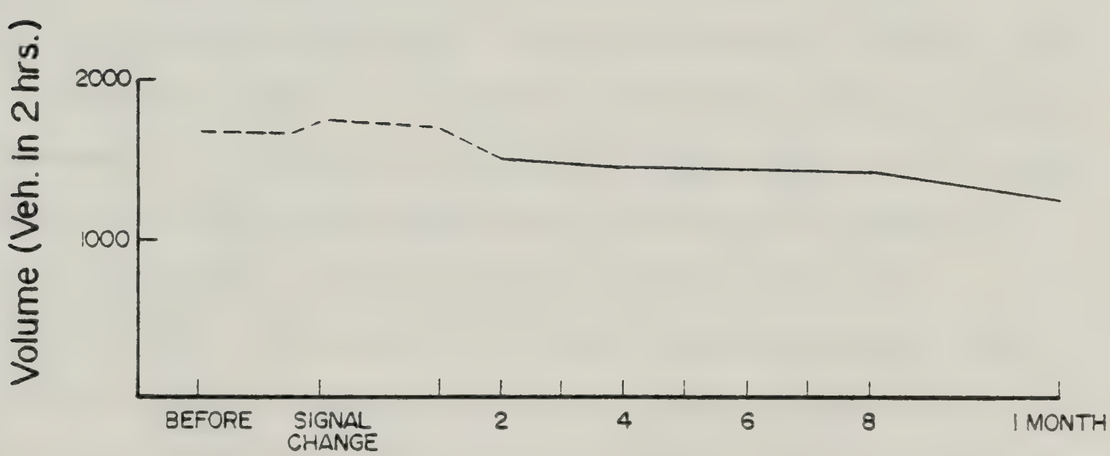


Figure IV.23 Development of Equilibrium – Northbound Through Lanes – Stony Plain Road and 142 Street

Unfortunately, traffic volumes 'before' (June) and one month 'after' (December) were 10 to 15% lower than volumes that existed when the construction was completed in November, 1979. As a result, delay and queue comparisons in this section are between October and November data, even though the signal change was in effect in October.

A 'before' and 'after' comparison of average delay for both through and right turn lanes (Figures 4.24 and 4.25) indicates a reduction in delays for both lanes, with the right turn having the largest improvement. The queue length comparison (Figures 4.26 and 4.27) also indicates a major reduction in queueing for the right turn lane (40 veh).

In the 'before' case, delays for the right turn were comparable to delays for traffic continuing through and using a 'shortcut' route to access Stony Plain Road. In the 'after' case, the removal of delays for right turns removed an incentive to 'shortcut'. As a result, through volumes have been reduced, resulting in improved operations. The 'before' data here does not reflect the severity of through delays that occurred during the highest volume conditions, as data was collected after the signal phasing change in October, 1979.

Peaking characteristics 'before' and 'after' are compared in Figures 4.28 and 4.29. It be seen that most of the increase in right turns during the peak hour was paralleled by a decrease in northbound through traffic in the adjacent lanes. This effect was further encouraged due to the ability of motorists to view queues in both through and right turn lanes at the same time.

In the short term, total volume on the south approach to Stony Plain Road - 142 Street did not change. An intersection count conducted in September, 1980, indicated that AM peak period volumes have increased by 2% (from 3694 to 3769 vehicles) on the south approach since November, 1979. Morning peaking characteristics for the northbound right turn lane have remained similar to those for November, 1979, as delays have remained low for this movement. This indicates that, even in the long term, only a localized impact to traffic flows has occurred.

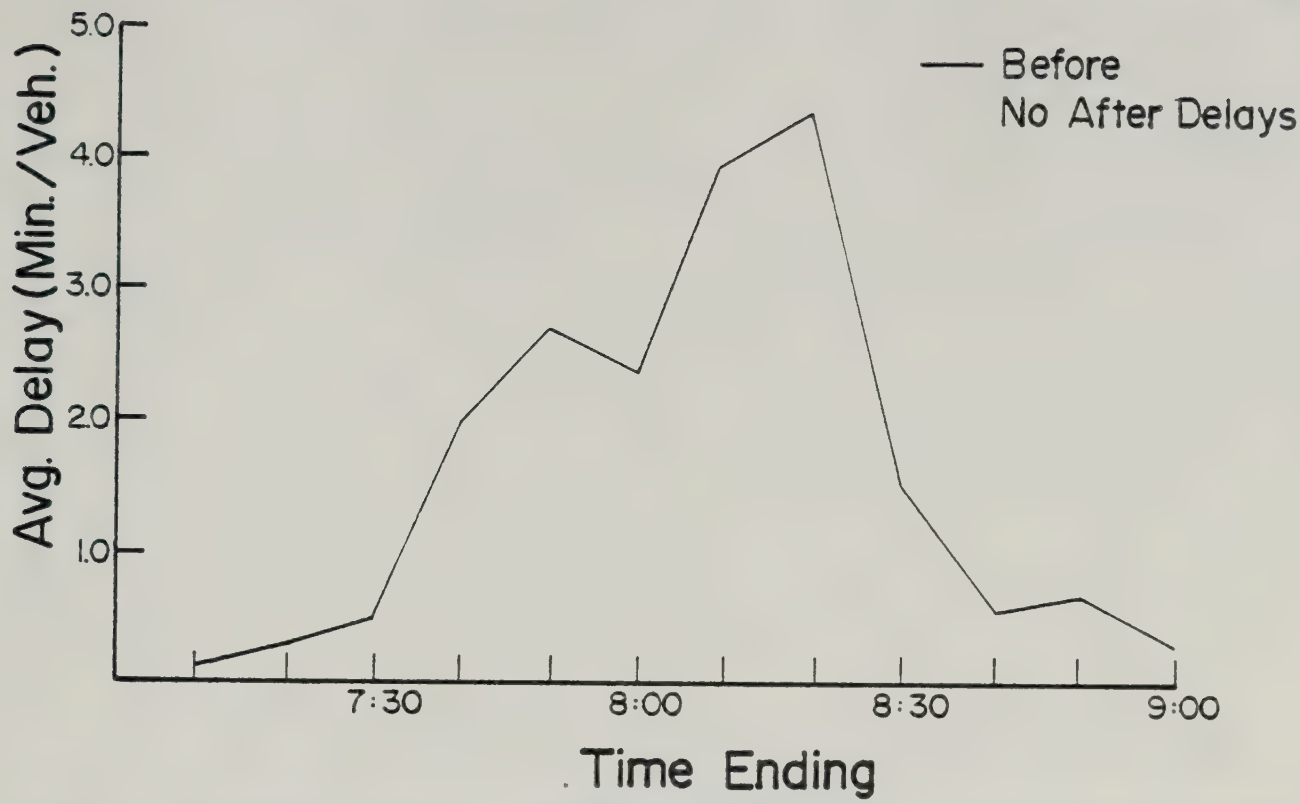


Figure IV.24 Vehicular Delays - Northbound Right Turn - Stony Plain Road and 142 Street

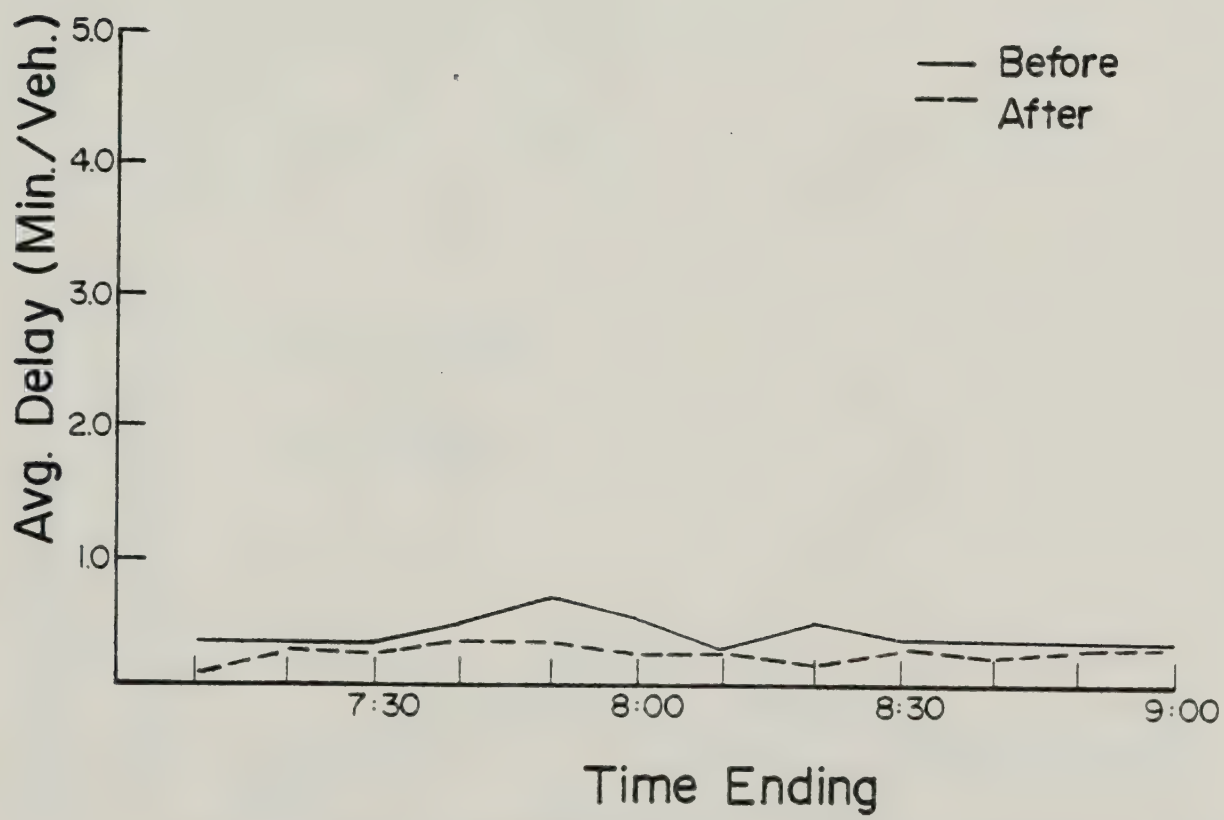


Figure IV.25 Vehicular Delays - Northbound Through Lanes - Stony Plain Road and 142 Street

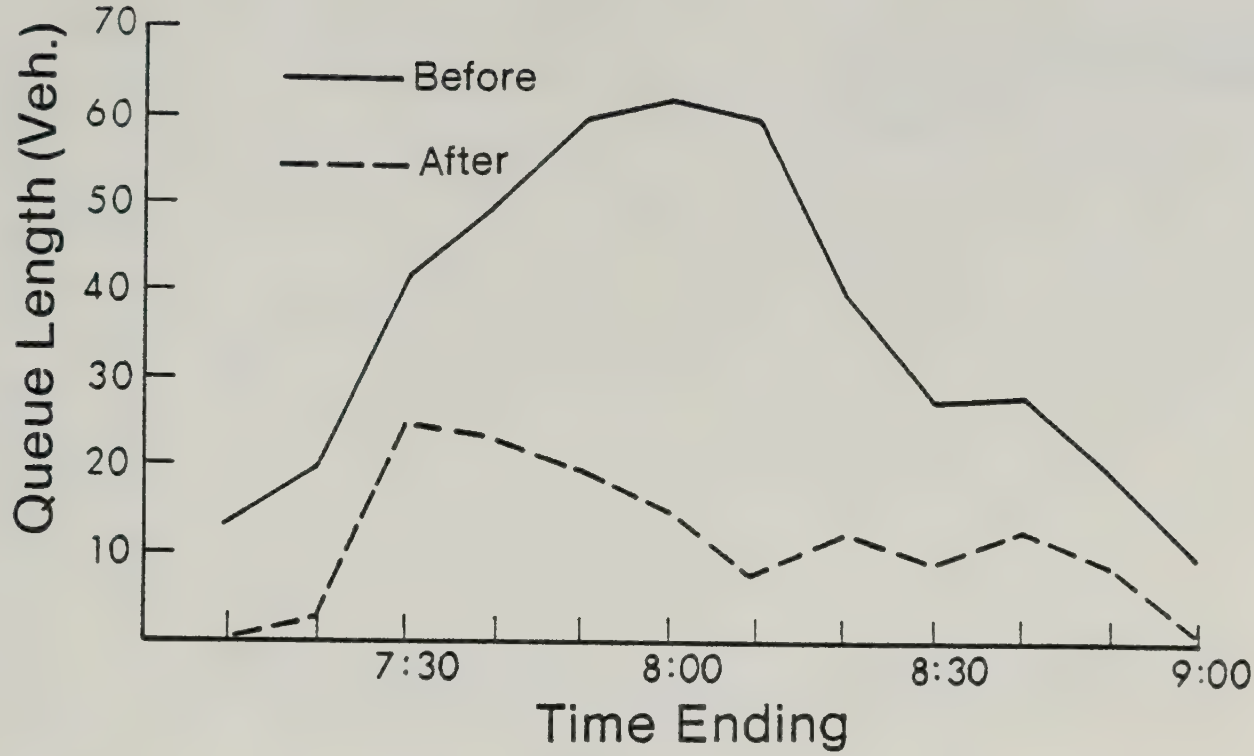


Figure IV.26 Queueing - Northbound Right Turn - Stony Plain Road and 142 Street

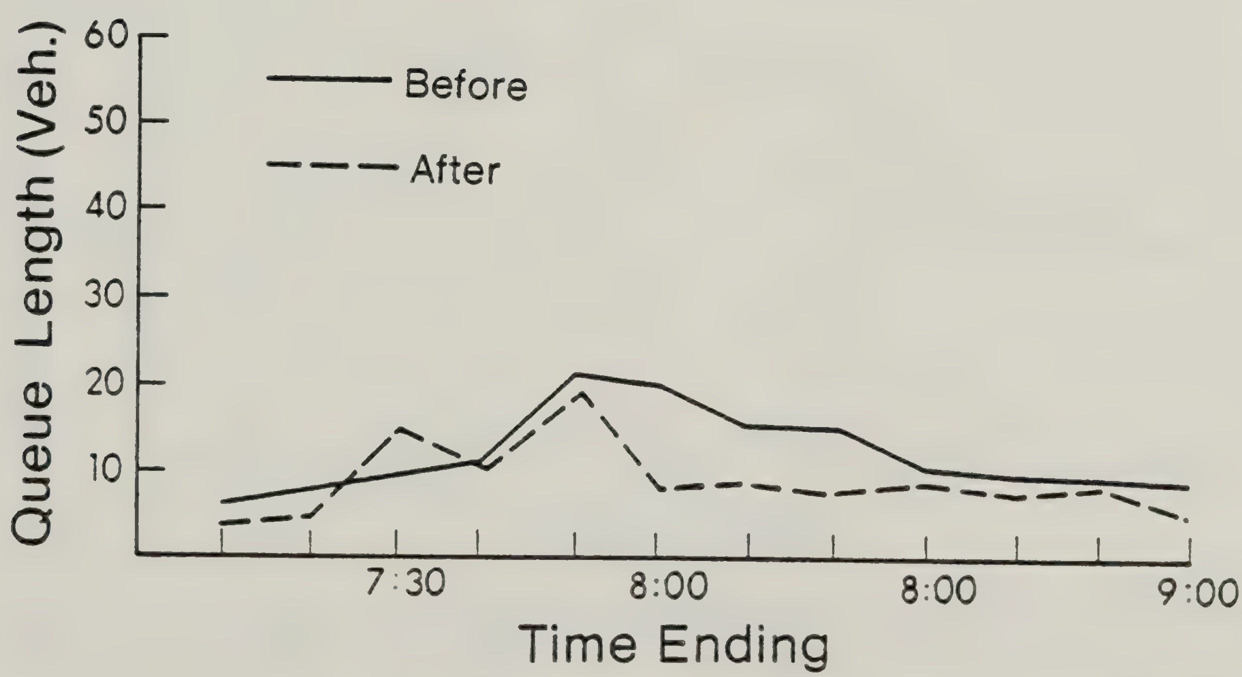


Figure IV.27 Queueing - Northbound Through Lanes - Stony Plain Road and 142 Street

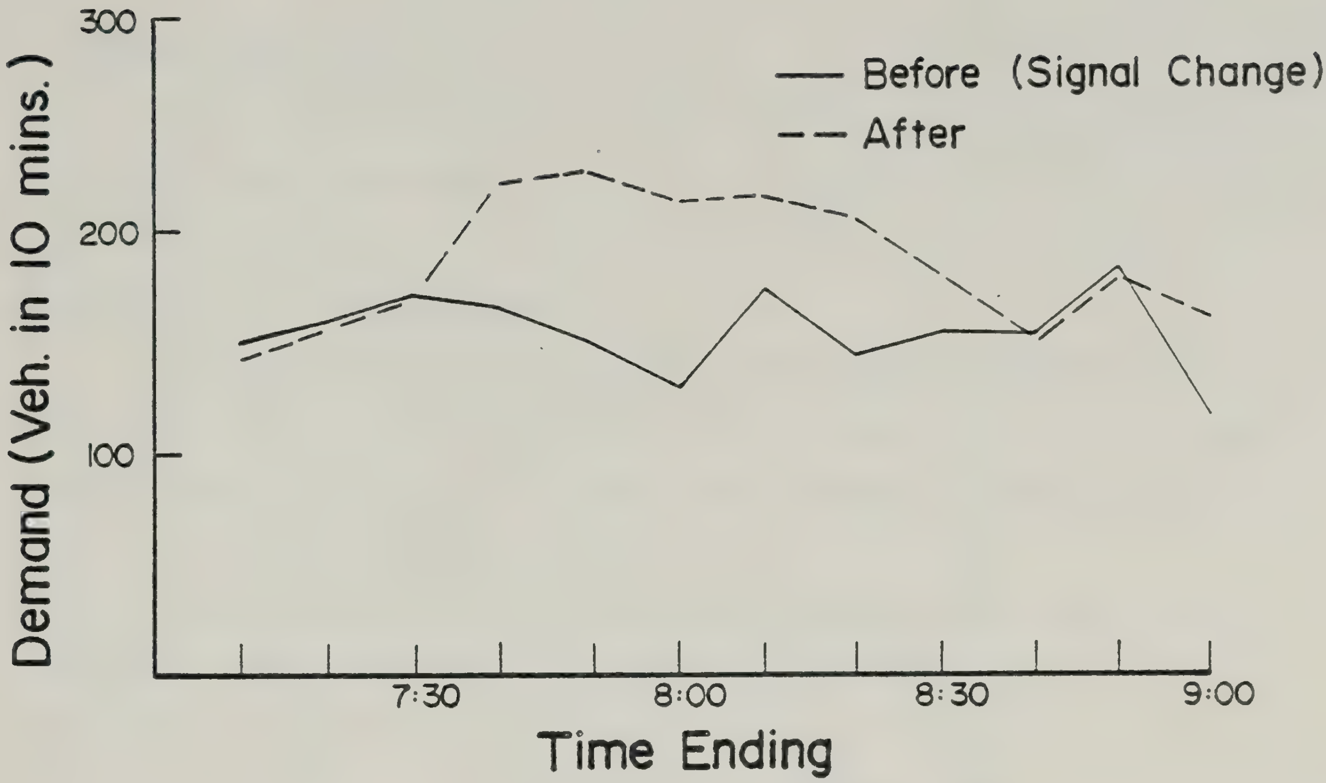


Figure IV.28 Peaking Characteristics - Northbound Right Turn - Stony Plain Road and 142 Street

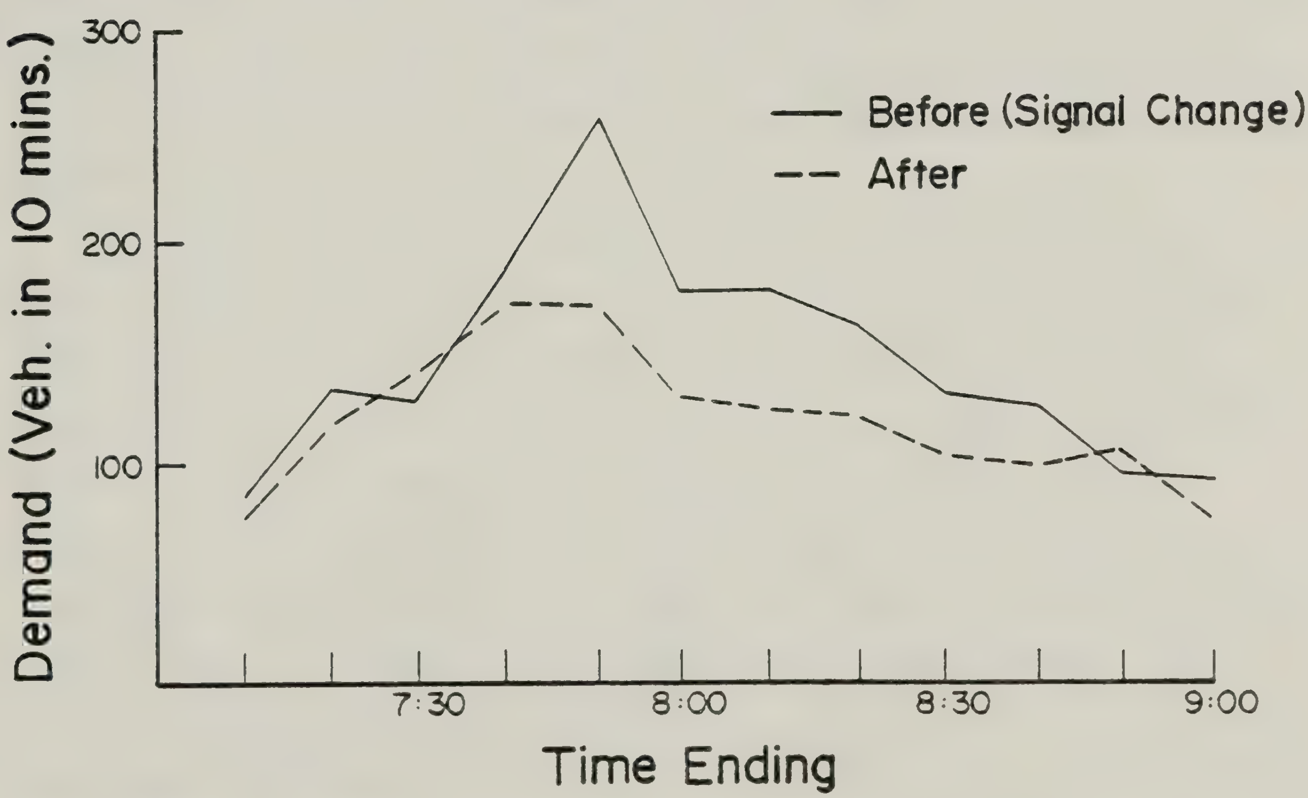


Figure IV.29 Peaking Characteristics - Northbound Through Lanes - Stony Plain Road and 142 Street

C. Individual Travel Behaviour

Individual travel behaviour was studied primarily through the analysis of license plate survey results. Mode choice was evaluated only for Kinnaird Bridge, temporal assignment for Fort Road – 66 Street and Kinnaird, and route assignment for all three study areas.

License plate surveys matching 'before' and 'after' data indicated a match rate between 40%, for Fort Road, and 57% for Kinnaird. Non–matching vehicles may have resulted from errors in license plate recording, vehicles shifting in or out of the study area, or different vehicle sets.

The expected match rate in license plate surveys is near 80%. Comparing 'before' and 'after' data separated by up to six months, one would expect a lower number of matches. Flow comparisons show little difference between total volumes 'before' and 'after', indicating that few vehicles shifted in or out of the study area. Different vehicle sets would be most likely in the Fort Road – 66 Street area, where the survey of PM peak trips included many shopping trips. When comparing shopping trips made on different days, one would expect that, although the number of trips may be the same, the vehicles actually making the trips would be different. In this case, license plate surveys would show few matches.

To perform an analysis of temporal assignment, license plate surveys were performed on July 28 and July 30, 1981 (from 6:45 to 8:45), on 82 Street south of 112 Avenue. A comparison of data for these two days was used to provide a 'typical' daily distribution of times that vehicles pass a survey station. The results of these surveys suggested that, on average, 50% of vehicles travel within the same 5 minute time interval, or the 5 minute interval immediately preceding or following the 'before' time interval. This data was then used as a basis for comparing license plate data from the Fort Road – 66 Street and Kinnaird areas.

a Fort Road - 66 Street

The 'before' and 'after' route selection in this study area is shown in Figures 4.30 and 4.31. It appears that 66 Street has experienced major flow

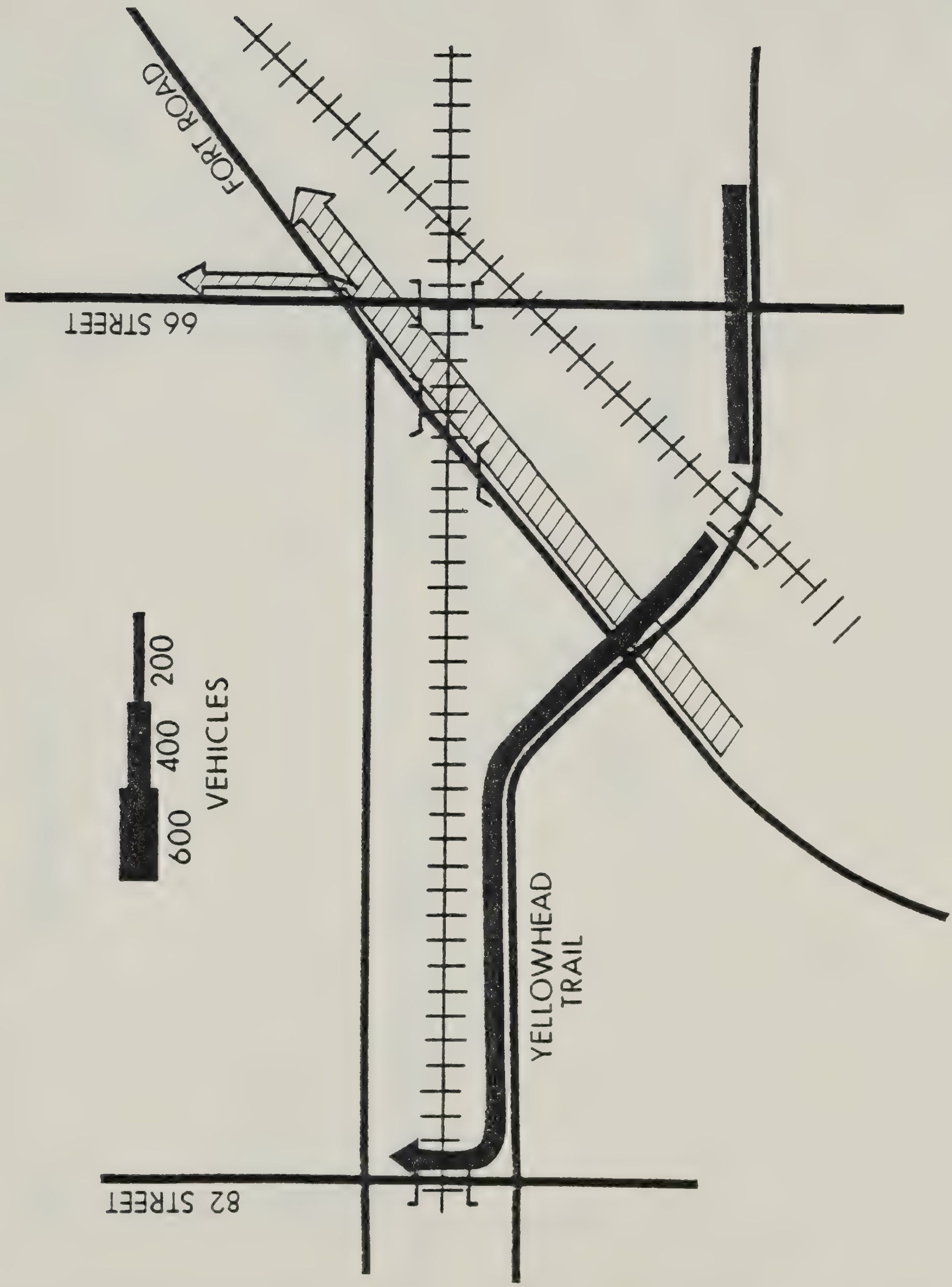


Figure IV.30 Route Selection 'Before' - Fort Road and 66 Street

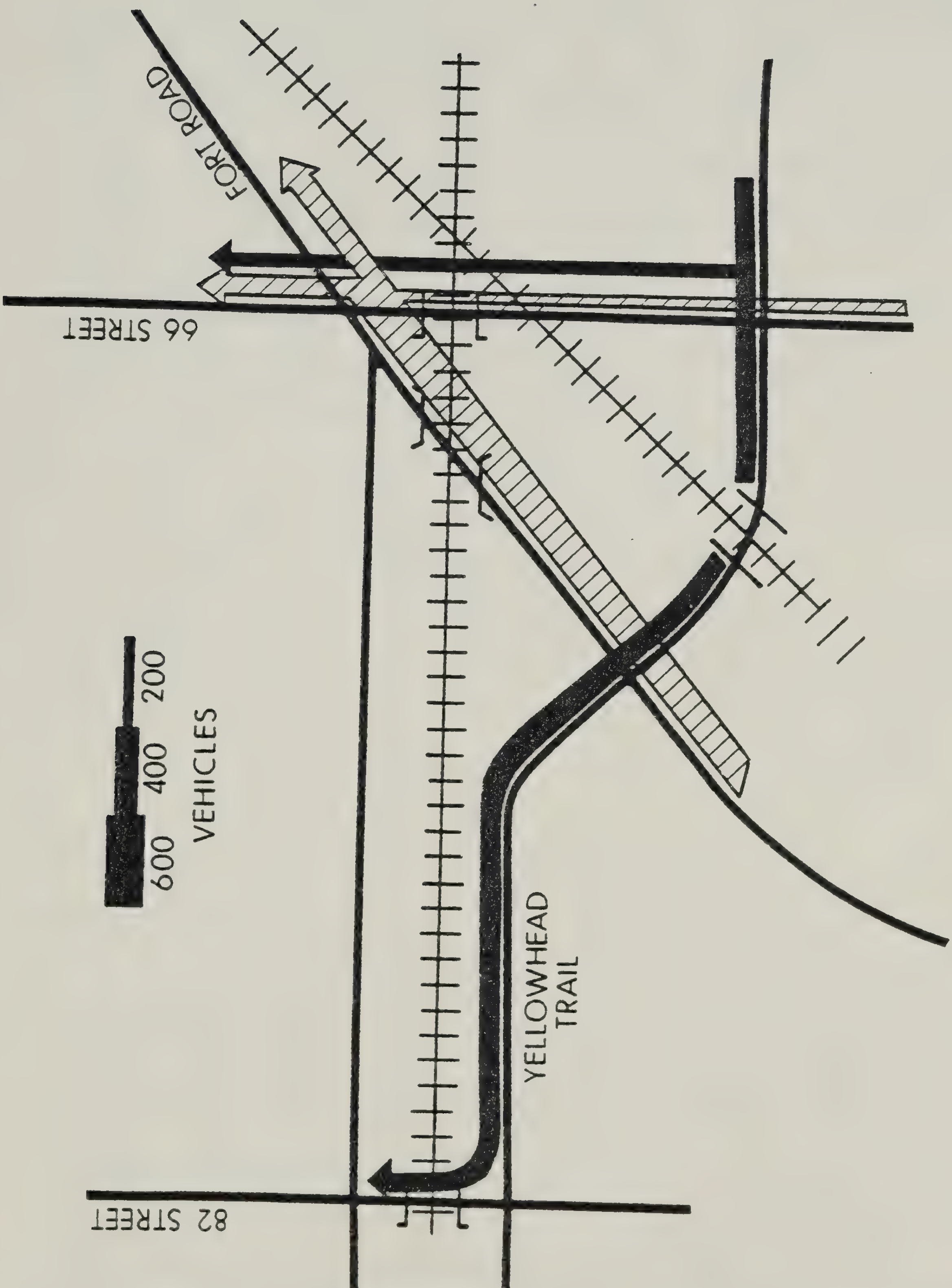


Figure IV.31 Route Selection 'After' - Fort Road and 66 Street

increases as a result of the diversion of trips from both Yellowhead Trail and Fort Road. The numerical results of the license plate matches are shown in Table 4.8.

Trips using Fort Road northbound, before the traffic management plan, had major trip origins in either the south Industrial area, or the central business district. Following the delay reductions on 66 Street, traffic from the south found 66 Street to be a shorter route than Fort Road to the northeast area. The trips that diverted from Yellowhead Trail to 66 Street have done so to avoid long delays in the vicinity of the 82 Street railway underpass. These trips have the north or northwest areas as destinations.

Figure 4.32 illustrates the distribution of travel times past stations on 66 Street and Fort Road. Unfortunately, no 'base' daily fluctuations for the PM peak were measured. It appears that less than 60 % of 'before' traffic has travelled in the same time interval 'after'. It would be expected that a smaller proportion of vehicles would remain in the same time interval than in the AM peak, due to the presence of trip purposes other than work to home.

Examining Figure 4.32, the only points where temporal re-assignment may have occurred (as given by less than 30% of vehicles travelling within the same time interval) are:

a. 66 Street - between 16:35 - 16:45, and 17:25 - 17:35

b. Fort Road - after 17:30

These results are considered to be inconclusive.

b Kinnaird Bridge

Figures 4.33 and 4.34 illustrate route selection 'before' and 'after' the Kinnaird Bridge closure. For flows from the north, shifts have occurred from 82 Street to both Stadium Road and 95 Street. Due to overloading of Stadium Road, a shift to 95 Street is observed for trips that formerly used Stadium Road.

The license plate surveys in Kinnaird were conducted more than one month after the bridge closure. By this time, the control revisions on 112 Avenue (additional lane) had been in place for some time. 112 Avenue volumes

Table IV.8 Route Selection Fort Road and 66 Street

Before	After	Match	Vol. Before	Vol. After
66 St	66 St	367	1748	2491
Fo Rd	Fo Rd	536	1976	1868
Fo Rd	66 St	229	1964	2491
82 St	66 St	120*		

* est.

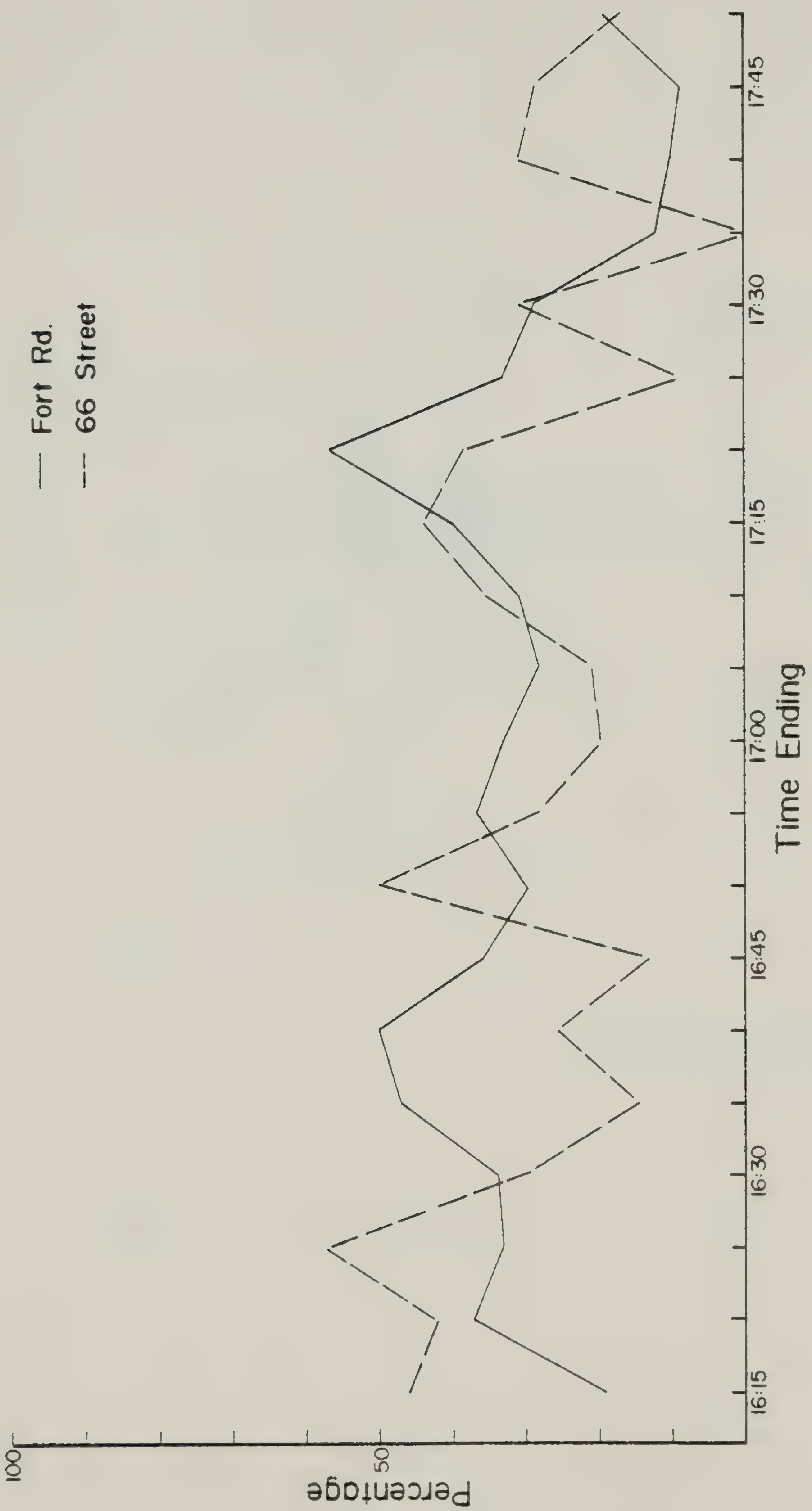


Figure IV.32 Temporal Re-Assignment - Fort Road and 66 Street

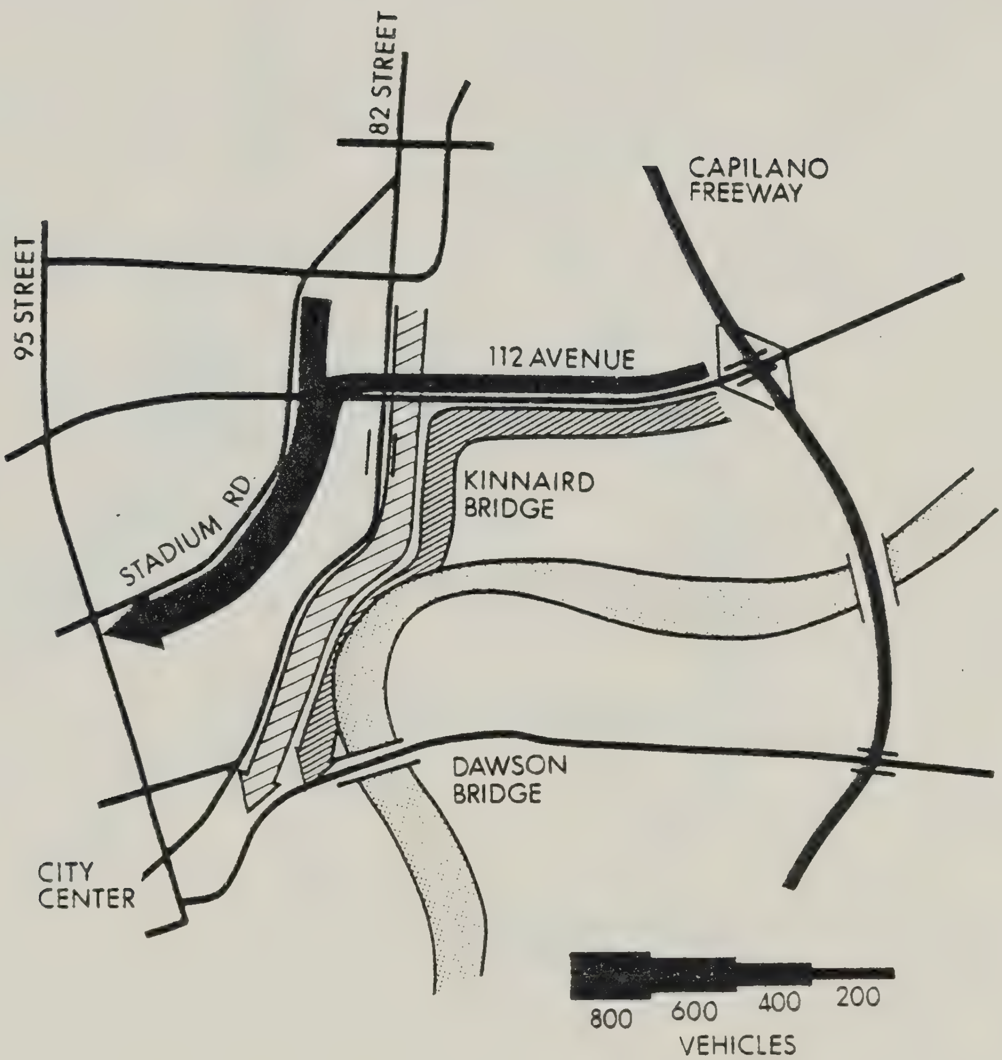


Figure IV.33 Route Selection 'Before' – Kinnaird Bridge

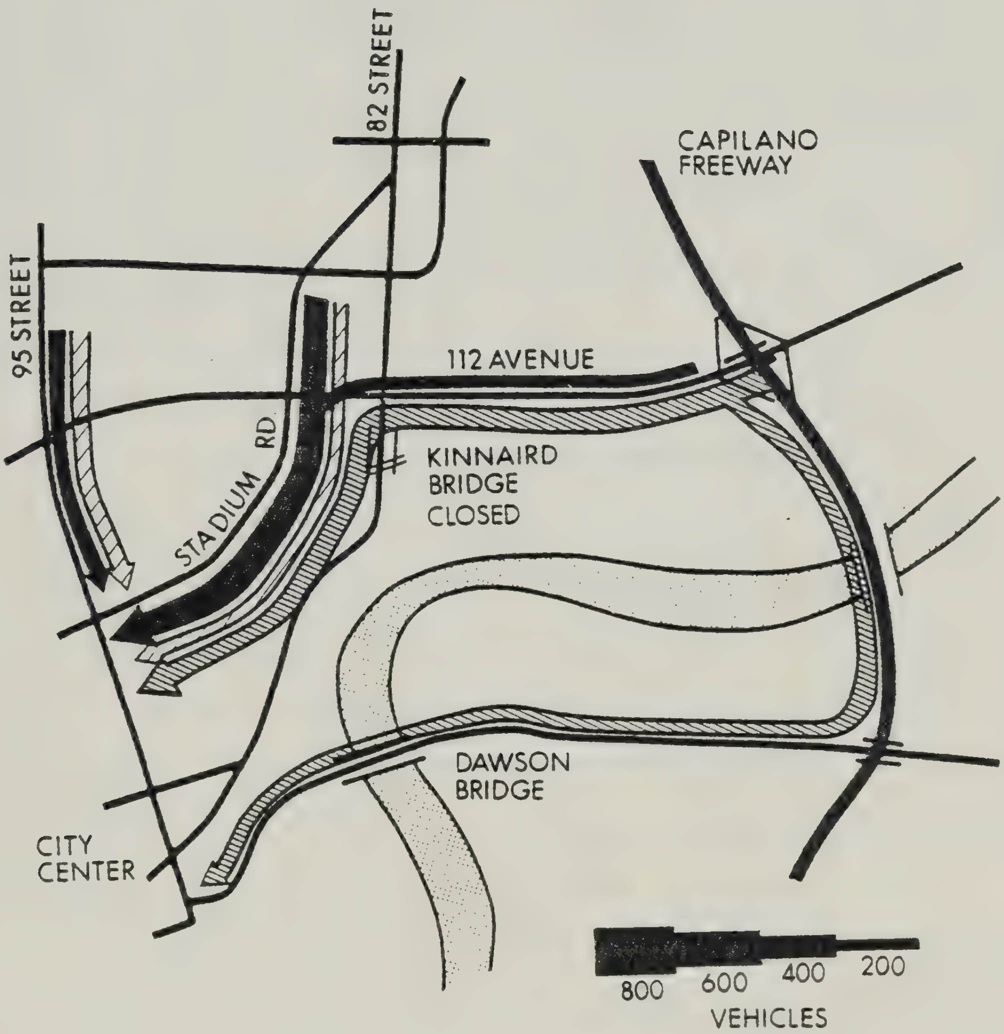


Figure IV.34 Route Selection 'After' - Kinnaird Bridge

had increased somewhat from the period immediately after the detour began. The traffic control change on 112 Avenue did result in some vehicles returning to 112 Avenue from the 106 Avenue / Dawson Bridge route. Numerical results of license plate matches are shown in Table 4.9.

Figures 4.35 and 4.36 illustrate the proportion of 'before' vehicles travelling within 10 minutes of their before arrival time in the 'after' survey. In both cases, 1979 license plate survey matches are compared with the typical daily fluctuations measured in July, 1981. These typical daily fluctuations, measured on 82 Street south of 112 Avenue, are taken to be representative of the Kinnaird area in the A.M. peak period. In general, between 40% and 80% of vehicles selected the same time interval, or travelled in the 5 minute interval adjacent to the previous time of travel.

For flows from the north, 'before' and 'after' matches of traffic on 95 Street and Fort Road were performed. On 95 Street, between 30% and 70% of 'before' traffic travelled at the same time 'after', matching closely the typical daily pattern. In general, the results for Fort Road also fall into this 30% to 70% range. Fort Road results for the times ending 7:55, 8:10 and 8:25, show less than 30% of vehicles travelling at the same time. Additional 'before' and 'after' temporal matches were conducted for flows that shifted (ie 82 Street 'before' to 95 Street 'after'). These results were inconclusive, due to a small sample size, which caused a wide fluctuation in results.

Flows from the east do provide evidence of temporal re-assignment. Results for the Dawson Bridge station closely match typical fluctuations, with between 40% and 70% of vehicles travelling at the same time. For traffic on 112 Avenue, a much higher proportion than expected has shifted from the previous time of travel. This behaviour is confined to the period from 7:30 to 8:05, when less than 30% of traffic travels at the same time. This corresponds to the time at which traffic counts indicated that the traffic peak was flattened along 112 Avenue. The temporal re-assignment at this location is still in evidence, despite the fact that license plate surveys were conducted two weeks after the barricades had been removed on 112 Avenue. As a result, delays on

Table IV.9 Route Selection - Kinnaird Bridge

Before	After	Match	Vol. Before	Vol. After
Ja Ave	Sta Rd	571	1969	2164
Ja Ave	95 St	376	1969	2011
Sta Rd	Sta Rd	510	1356	2164
Sta Rd	95 St	212	1356	2011
112 Av	112 Av	620	1944	1891
112 Av	Dawson	229	1944	1844
82 St	For Rd	257	1969	1161

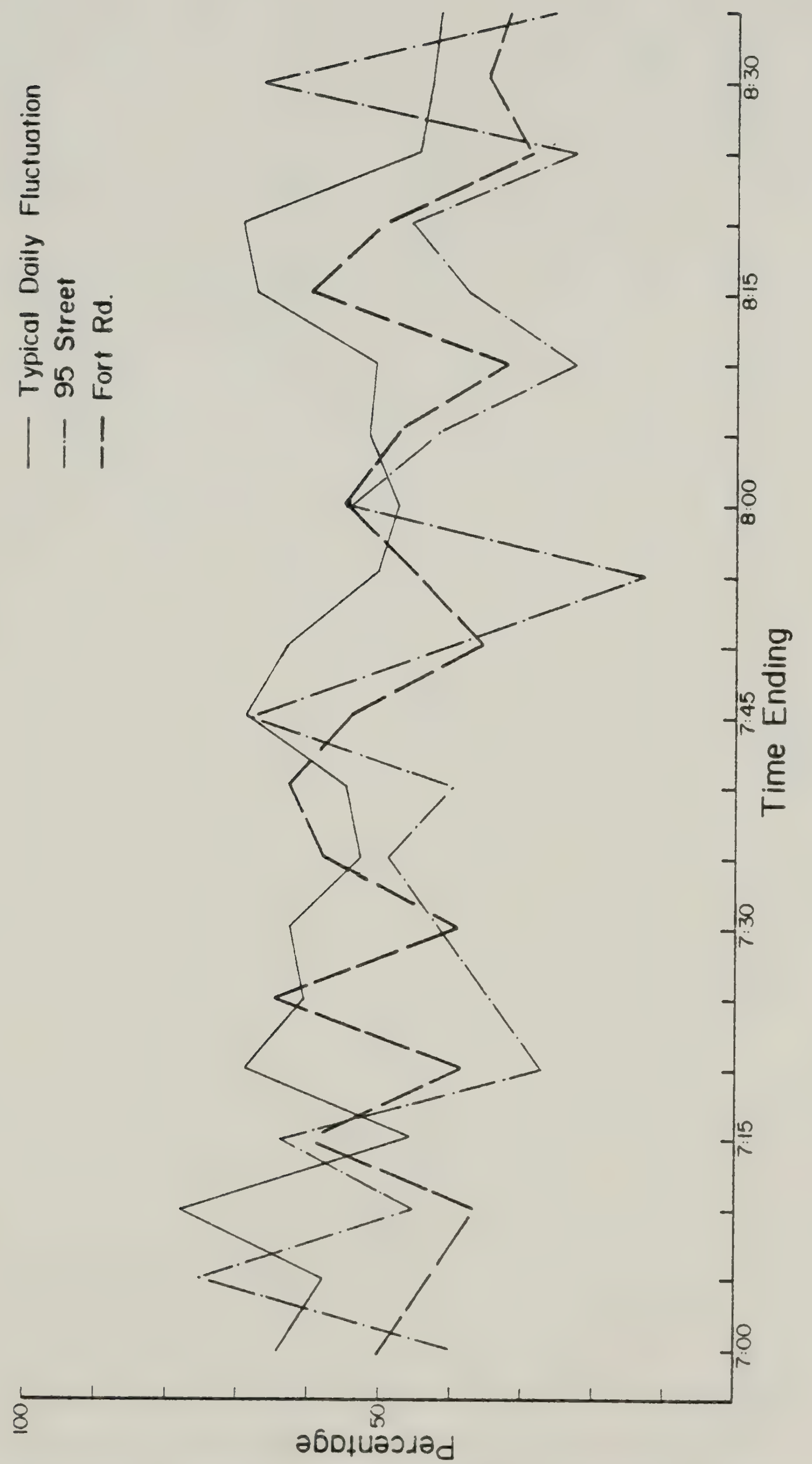


Figure IV.35 Temporal Re-Assignment - Kinnaird - Flows from the North

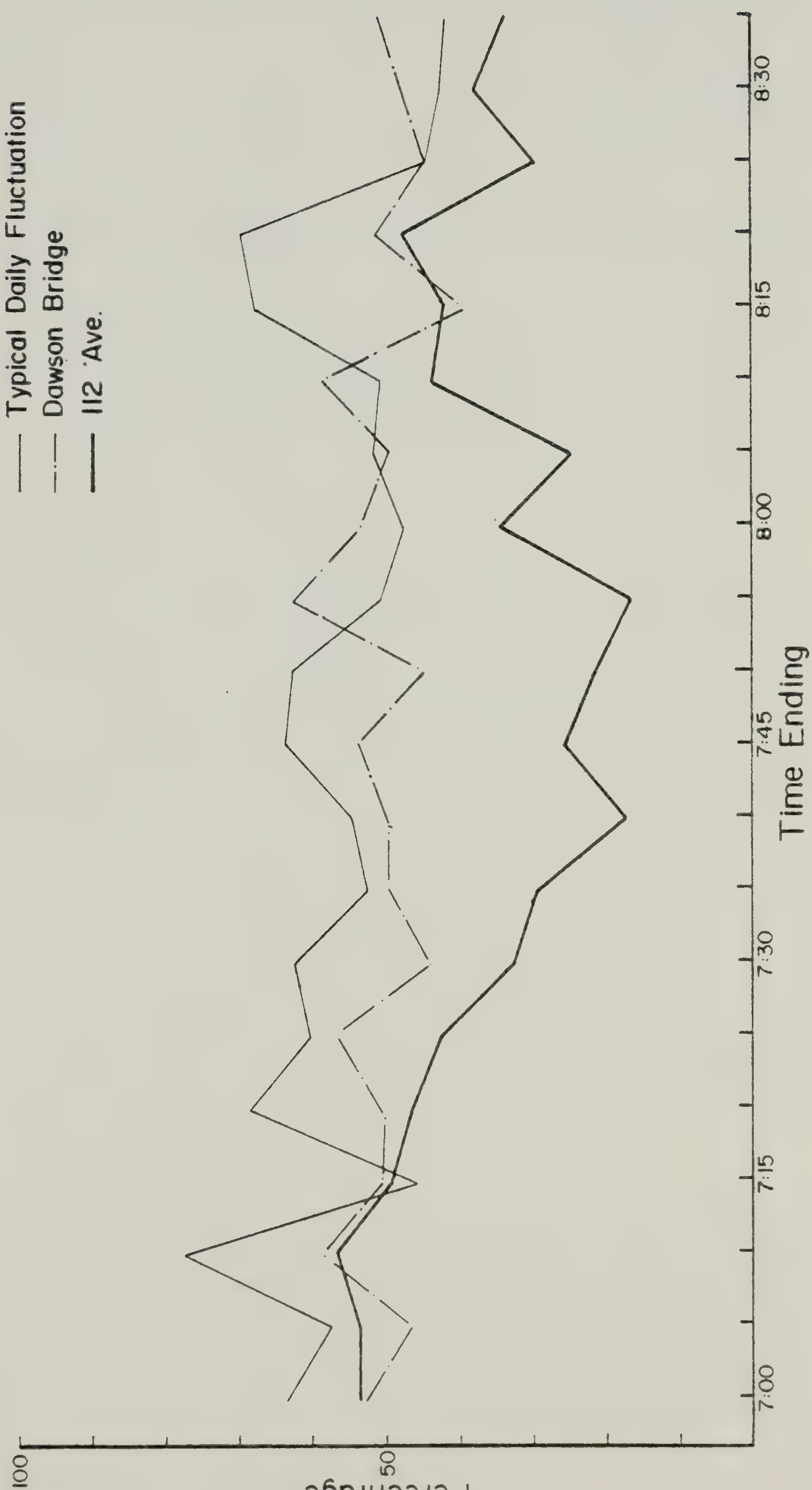


Figure IV.36 Temporal Re-Assignment – Kinnaird – Flows from the East

112 Avenue at the time of the license plate survey had been reduced by 4 to 5 minutes in the peak hour.

No change in Light Rail Transit ridership was apparent within the first week after the Kinnaird closure began. AM peak L.R.T. ridership remained 4000 passengers (between 6:30 and 9:00), inbound. Possible reasons for no change in L.R.T. ridership are:

a. mode re-assignment did not occur, as an insignificant change occurred in relative auto and transit travel times

b. mode re-assignment did not occur due to the temporary nature of the Kinnaird detour

The results suggest that mode re-assignment might have occurred if the detour would have lasted for a longer period of time. Further data at other locations is required before any conclusions could be made about the influence of network changes on modal choice.

c Stony Plain Road - 142 Street

Although no license plate surveys were conducted in the Stony Plain Road - 142 Street area, an analysis of volume data indicates that some change in driver route selection did occur in the immediate vicinity of the traffic management plan. 'Before' and 'after' volume comparisons indicate:

a. No change in total volumes on the south approach to Stony Plain Road - 142 Street occurred during the AM peak period.

b. No change in total eastbound volumes on either Stony Plain Road or 102 Avenue was observed at 124 Street.

c. At Stony Plain Road - 142 Street, northbound right turns in the peak hour increased by 300 veh/hr, while northbound through traffic decreased by the same amount.

The only reasonable explanation for the volume changes observed near Stony Plain Road - 142 Street is that the traffic management plan has displaced 'shortcutting' traffic from local streets back to the arterial roadways. This change in route selection 'before' and 'after' is illustrated in Figures 4.37 and 4.38.

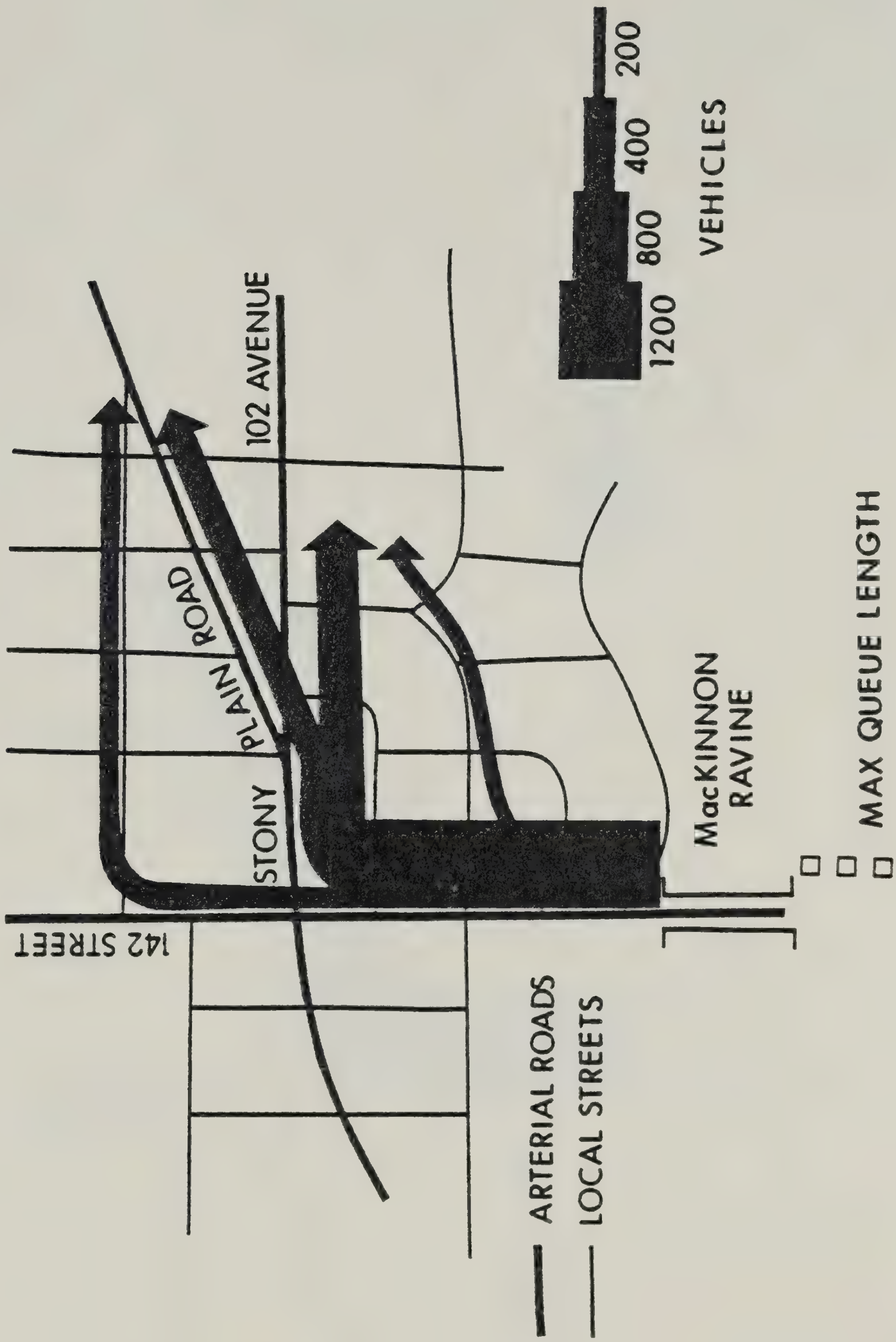


Figure IV.37 Route Selection 'Before' - Stony Plain Road and 142 Street

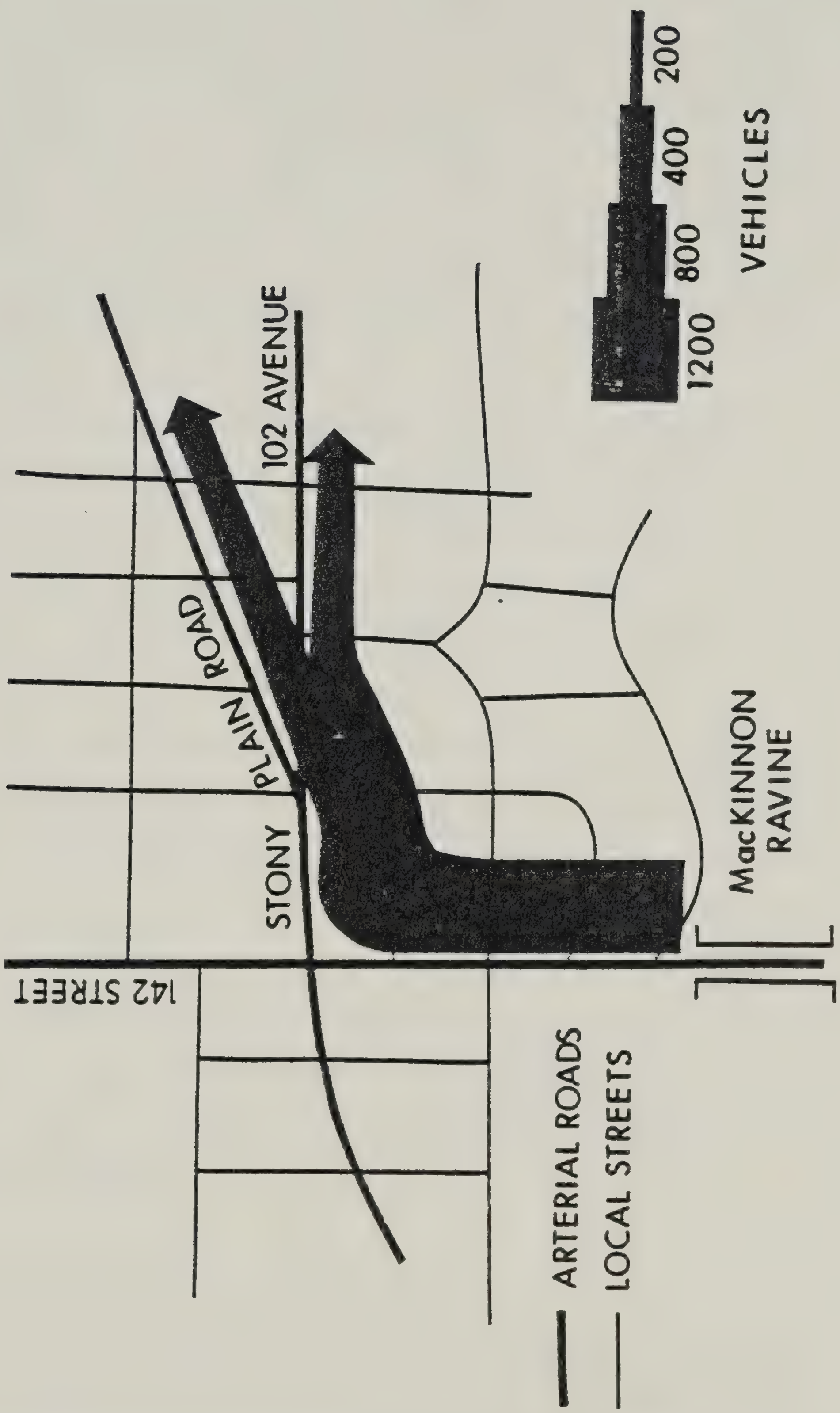


Figure IV.38 Route Selection 'After' – Stony Plain Road and 142 Street

The attraction of 'shortcutting' traffic from local streets back to the arterial roadways may be attributed to two factors. First, and most important, the conversion of the curb lane of 142 Street to free flow conditions, with no significant delays or queueing, resulted in a removal of the incentive for traffic to shortcut. At the same time, 'after' delays for through traffic were longer than that for the right turning traffic (15 seconds versus no delay).

Traffic that approached 142 Street from the south would be expected to make the decision to 'shortcut' based on prevailing traffic conditions. If the right turn queue was short, or non-existent, vehicles would tend to remain on the arterial route (Stony Plain Road), as this would be the quickest route to the east.

It is possible that temporal re-assignment did occur on the south approach to Stony Plain Road - 142 Street in the short term. The proportion of total northbound demand within the peak hour increased from 55%, in the 'before' case, to 61% in the 'after' case. This in itself does not to provide sufficient evidence to conclusively show that temporal re-assignment has occurred.

The Stony Plain Road - 142 Street traffic management plan provided good evidence of the importance of acceptable arterial operating characteristics in discouraging 'shortcutting' traffic. A reduction in flows of 300 vehicles per hour represents a significant improvement for residents on local residential streets. The results of this traffic management plan also point out the necessity of including local streets when evaluating the impact of transportation management measures. The reduction in 'shortcutting' achieved at Stony Plain Road - 142 Street was not foreseen when the traffic management plan was originally developed.

D. Summary of Results

The results presented in this chapter indicate that perceptible changes in network operation and travel behaviour occur as a result of network changes (such as the implementation of T.S.M. plans).

The key results of the Edmonton studies are that changes in the network and network operating characteristics do cause travel behaviour changes. Many results were common to all study areas, but some results were only noted at particular locations. The Edmonton surveys led to the following results:

a Findings Common To all Areas

1. A combination of queues, intersection delays and travel time are important influences on travel behaviour.
2. Route re-assignment was noted following a change in network capacity, queues and delays.
3. A change of 3 minutes in route travel time induced significant traffic rerouting.
4. A change in queue lengths of 40 vehicles per lane results in significant traffic rerouting.
5. Traffic rerouting was observed with both an increase and a decrease in route travel times.
6. Peaking characteristics were observed to change only when travel time changed by over 4 minutes and/or queue length changed by over 40 vehicles.
7. Conclusive evidence of temporal re-assignment was confined to one route within the Kinnaird study area.
8. No evidence of further changes in route assignment over the long term were noted.

b Findings of Specific Study Areas

1. A queue length reduction of 40 vehicles resulted in the elimination of a neighbourhood 'shortcutting' traffic problem at Stony Plain Road - 142 Street.
2. In the Kinnaird area, no change in mode selection was observed following the closure of Kinnaird bridge.
3. In the Kinnaird area, drivers were reluctant to switch to the 106 Avenue / Dawson Bridge route, possibly due to two river crossings.
4. At Fort Road - 66 Street, volume stability occurred within two weeks

after the traffic management plan was in place.

5. Equilibrium was re-established in the Kinnaird Bridge area within one week 'after' the detour commenced. It is not known whether this was a stable equilibrium pattern.
6. Peaking characteristics began to change several days after route re-assignment began for flows from the east and north in the Kinnaird area.
7. Temporal re-assignment was confirmed for westbound traffic on 112 Avenue, in the Kinnaird area. This occurred as a result of travel time changes exceeding 4 minutes per vehicle.

V. CONTRAM SIMULATION

In Chapter 2, a review of the state of the art in traffic modelling was presented. It was shown that a number of new models are now being developed that attempt to combine a traffic assignment with detailed traffic engineering and signal optimization.

The University of Alberta was able to obtain, in 1979, a copy of the pre-release version of CONTRAM, from the Transport and Road Research Laboratory for research purposes. As yet, official release of CONTRAM has not occurred. It was felt that the Kinnaird Bridge study area would form a useful test of CONTRAM, due to the extensive data collected in this network. In particular, the license plate survey data that was collected enables a direct determination of the origin-destination table for the network.

The analysis using CONTRAM attempted to calibrate the model to observed conditions. This calibration should reveal the difference in results caused by considering route assignment alone (ie ignoring temporal and modal re-assignment).

It is hoped that the experience of this use of CONTRAM may form a useful input into the continuing development of the model.

A. Theory

A description of the theory of CONTRAM is provided in detail in Road Research Laboratory report TRRL 841 (Ref. 29). Some of the more important aspects of data requirements, theory and program output are discussed in this section.

a Data Requirements

Three types of data sets are required for the execution of CONTRAM (Ref. 40):

Traffic demand data

Information on traffic demand is provided in the form of an origin-destination table indicating flows between up to 50 origins and 50 destinations. This information is provided for each time slice being simulated

in one run of the model. The size of these time slices can range between minutes and hours, and all slices need not be uniform. Flows between origin–destination pairs are loaded onto the network in packets of a size specified in the input data (typical packets are 10 vehicles). The option exists to constrain certain flows to specific routes between origins and destinations. This could be used, for example to simulate bus or truck routes.

Network data

The basic network description in CONTRAM is in the form of links and nodes, where nodes represent signalized intersections, origins or destinations. Three types of links can be modelled:

a. uncontrolled or free–flowing links
b. give–way links; used to represent stop or yield intersections, or used to simulate merging in a freeway or traffic circle (a single give–way link may yield to up to two uncontrolled links)
c. signal controlled links

For each link, information must be provided on link length, free running time, saturation flow, and, optionally, storage space. A single link may feed up to 5 links. The description for signal controlled links must also include the signal number and main phase on which the link discharges. The percentage of phase time may be adjusted to reflect such features as phase sharing or turning movements on gaps.

Control Data

For up to 50 signalized intersections, a number of signal timing plans may be specified. Allowing more than one timing plan at a signal enables the simulation of variable phasing, and different timing plans within each time interval. Signal timing details provide cycle time and effective green intervals. At each signal, the timing plan used during each simulation interval is specified.

The option exists to use timing plans with fixed cycle time and signal splits, optimized splits with a fixed cycle time, or both optimized

splits and cycle time. Optimized timings, if requested, make use of Webster's optimum cycle formula and determine signal splits by balancing degree of saturation.

The number of iterations of the model is specified in control data, with 5 iterations being a suggested minimum.

b Traffic Assignment

Figure 5.1 illustrates the procedures used for assigning flows in a CONTRAM network. Packets of vehicles are assigned, together, to the route of shortest travel time between an origin and a destination. After all flows have been loaded to the network, packets are re-assigned with the full knowledge of route delays. Test examples used by the Road Research Laboratory indicate rapid convergence after 2 or 3 iterations. Equilibrium assignment is not guaranteed by the model, but results should be close to the global optimum.

c Delay Calculation

CONTRAM uses route travel time as the only criteria when assigning traffic flows to routes in the network. The initial queue and delay times are provided for each time interval as outputs of the program. Travel time consists of three components:

Free Running Time

This quantity is directly input to the model.

Signal Delay

The delay at a signalized intersection consists of uniform and random delay. These are given by:

$$d = (c(1 - Q/s))^2/2(1 - q'/s) + 36(5*q''/(Q - 4)^2)$$

where:

d - delay

c - cycle time

s - saturation flow

Q - capacity of link during the time interval being studied

q - initial queue plus arriving flow in the time interval being

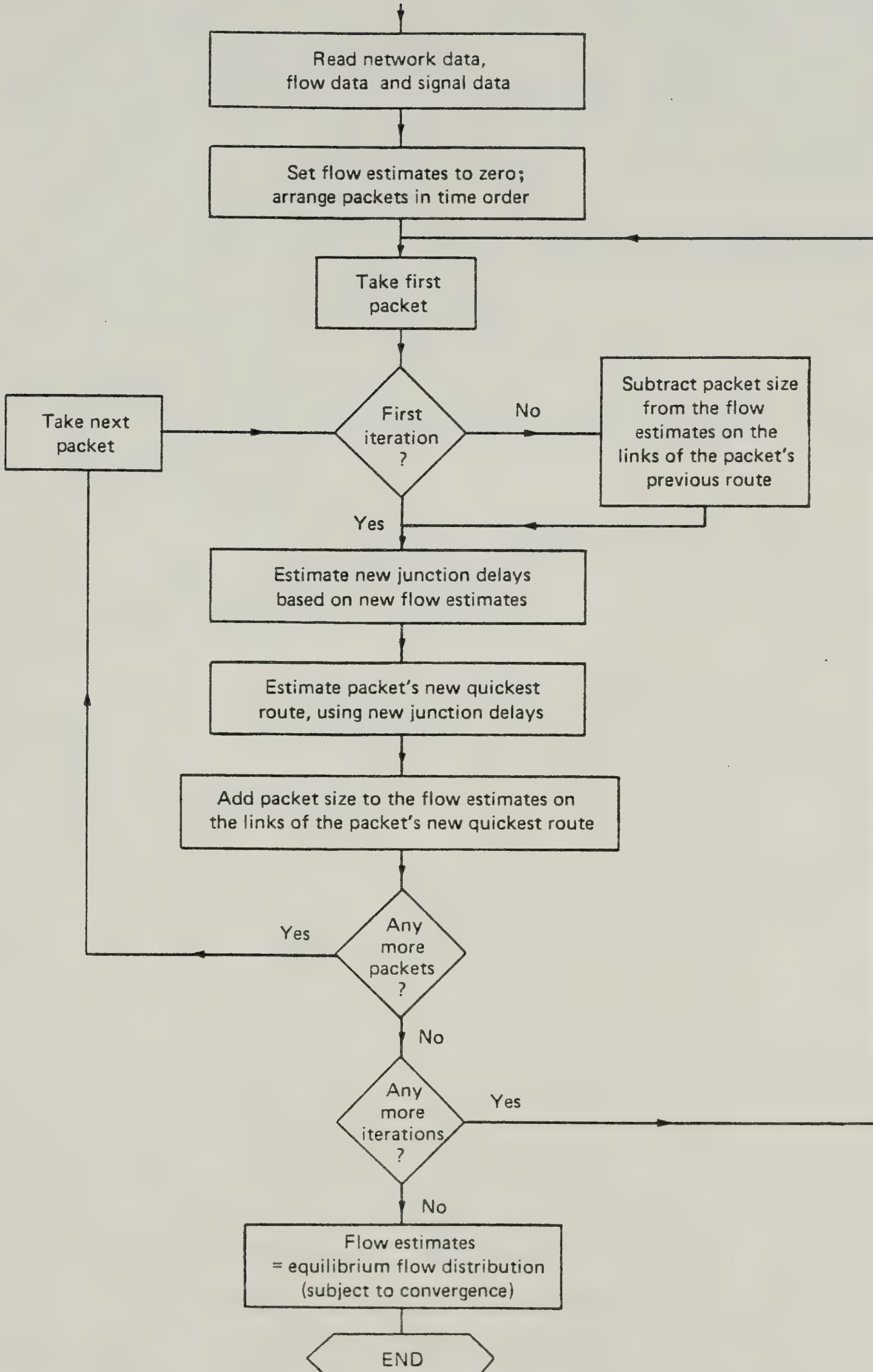


Figure V.1 CONTRAM Traffic Assignment (Source: Ref. 29)

studied

q' - the smaller of q or Q

$q'' = .8*Q$, if degree of saturation is less than 80%

= the smaller of q or Q if degree of saturation exceeds 80%

The uniform delay term here corresponds to that obtained from queueing theory, while random delay uses a model similar to that found in TRANSYT 5. Under saturated conditions, the form of the equation is such that only uniform delay increases.

Random delay on give way links uses the following form derived from queuing theory:

$d = q'/(2*Q(Q - q'))$

where q' is the lesser of q or 95% of Q (the link capacity in the time interval being simulated

Oversaturation Delay

For packets entering a link which has an initial queue, oversaturation delay represents the additional time required before vehicles delayed in queue can exit from the link. For uncontrolled links, oversaturation delay is the only delay that is considered.

The effect of a co-ordinated signal system is taken into account manually. For each link that is co-ordinated, the percentage of signal delay assigned to the link is reduced by some pre-determined value.

B. Network Description

For the Kinnaird Bridge area, two basic situations were analyzed; the full network prior to the bridge closure, and a revised network representing conditions 'after' the closure. These two examples allowed an evaluation of the performance of CONTRAM in both undersaturated and saturated networks.

Figure 5.2 indicates the link - node diagram for the CONTRAM network. Ten signalized intersections, 8 origins and 5 destinations were included. Two priority ruled intersections (111 Avenue - 96 Street and 106 Avenue -

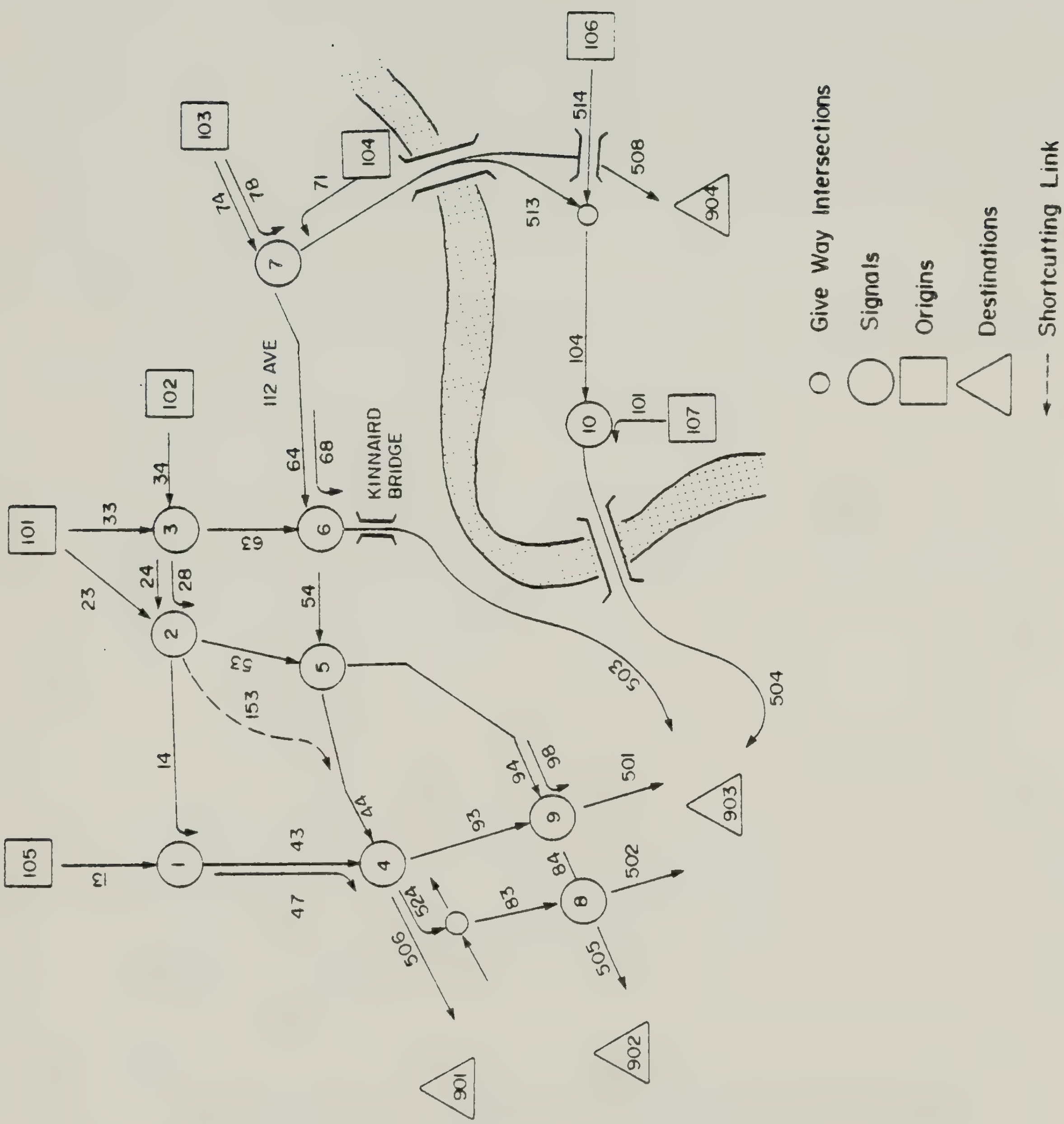


Figure V.2 CONTRAM Network - Kinnaird Area

Capilano Freeway) were simulated.

The network origin-destination table considered flows to the CBD from the north and east. Flows to two major arterials (107A Avenue and 111 Avenue) to the west, from the north and east were also simulated. The assumption made in the network representation was that flows from the west and destined to the CBD would have a minimal impact within the study area. This would include trips from 111 Avenue, Kingsway or 107A Avenue using 95 Street or 96 Street to access the CBD. Trips originating within the study area from residential areas north and west of the Northeast Light Rail Transit line were ignored in the analysis. This was expected to create some error and underestimation of flows at the destination end.

a Origin - Destination data

The origin-destination information used a combination of measured values from the license plate surveys, and assumed values:

origin 103 - 112 Avenue

License plate surveys conducted on 112 Avenue, and the intersection count conducted at 112 Avenue - Capilano Freeway indicated the following trip distribution:

zone 902 - 18%

zone 904 - 23%

zone 903 - 59%

No through trips to zone 901 were identified by the license plate survey matches. This result was accepted for purposes of this analysis. Practically, though, at least 5% of trips would be expected to travel through on 111/112 Avenue.

origin 104

All trips were assumed to be destined to zone 901.

origin 106 and 107

All trips were assumed to have zone 903 as a destination. To determine the magnitude of trips from zone 106, the 106 Avenue - 84 Street intersection count was used, subtracting trips from zone 103

indicated to use 106 Avenue by the license plate surveys.

origin 105

Trip percentages here were assumed to be 15% to zone 901, and the remainder to zone 903.

origins 101 and 102 (82 Street and 115 Avenue)

It was assumed that these origins both experienced the same trip distribution characteristics, as both flows have a common origin in northeast Edmonton. The trip distribution was determined by performing a balance of flows at the destination end. A balance of flows was found to exist when trips were split 15% to zone 901, 25% to zone 902, and 60% to zone 903. It is doubtful if better results could have been achieved with license plate survey results. License plate survey stations did not match the actual location of origins 101 and 102 as used in CONTRAM.

origin 202

A 'dummy' origin and destination along 111 Avenue were provided to enable a simulation of the give way link 524, simulating left turns across 111 Avenue eastbound onto 96 Street.

The flows entering the network from each origin made use of intersection counts conducted as part of the 'before' evaluation of Kinnaird (origin 105 had to use a 1978 intersection count at 118 Avenue - 95 Street). Flows were broken up into 15 minute intervals, covering the time period from 7:00 to 9:00, at each origin. Packet sizes of 10 vehicles were used, except for very small flows, where 5 vehicle packet sizes were used.

b Network Data

The basic network is as shown in Figure 5.2. Whenever exclusive right or left turn lanes existed, these lanes were simulated separately from the through lanes. This representation allowed a more accurate representation of network capacity.

Free link running time used observed network speeds (near the speed limit), with some adjustment for non-simulated intersections (ie 112 Avenue - 79 Street) and the Light Rail Transit crossings.

Saturation flows at signalized intersections were calculated using signal timings in existence at the time period being simulated, based on the City of Edmonton Saturation Flow Manual (Ref. 18), and measured capacities. Uncontrolled links feeding destination zones made use of the smaller of the capacity of the governing signalized intersection, or the link capacity (ie Dawson Bridge). Delay reductions to reflect co-ordination were only used on 112 Avenue, between 82 Street and 86 Street, as no signal co-ordination existed elsewhere in the network.

Certain minor connections within the network were ignored, as flows on these routes did not affect overall network capacity. These links include 92 Street (107A Avenue to Jasper Avenue), where measured volumes on 92 Street were combined with 95 Street volumes to permit a comparison to CONTRAM predictions.

c Control Data

Signal timings used in the Kinnaird CONTRAM simulation were the timings in place at the time period being examined. Only a single fixed time and fixed splits plan were used for each signal. As a result, some 'approximation' of actual timings had to be used to represent traffic-actuated signals in the area.

The fixed cycle and optimized splits feature was used during one analysis to compare the results with optimized timings to those with the timings actually used.

d Program Execution

Five iterations were permitted in each run of CONTRAM. Using the University of Alberta Amdahl 470 V-8 computer, simulations required between 17 and 20 seconds of computer time to complete, a time comparable to TRANSYT 7. The addition of timing optimization at 3 signals resulted in an increase of less than one second in required execution time.

C. Before Simulation

Conditions in the Kinnaird area prior to the bridge closure were such that almost all links were undersaturated. The 'before' simulation using CONTRAM confirms this result, with the maximum queue in the network being 14 vehicles on link 68 (112 Avenue WBD turning onto Jasper Avenue). Table 5.1 indicates the discrepancy between peak hour (7:15 - 8:15) predicted and actual demands for each link.

At entry points to the network, all predicted flows must equal actual demand. Table 5.2 compares predicted and actual travel times for the routes compared in Figure 4.9 for the Kinnaird area.

Total flows compared at outflow points from the network indicate a shortfall of 350 veh/hr. This error results from ignoring internal area trip generation, and ignoring flows from the west destined to the CBD (destination 903).

The magnitude of error on individual links is, in general, less than 10%, or 100 veh/hr. A difference of 10% or 100 veh/hr is the maximum acceptable range of daily traffic variations. Considering errors larger than this range, CONTRAM results differ significantly from measured volumes at the following locations:

a. 96 Street Sbd (links 524, 83 and 502)

As 96 Street forms the west boundary of the study area, this route is most likely to have a serious error due to flows from the west being ignored. The combined traffic from the west on 111 Avenue and 108A Avenue would contribute over 150 veh/hr of the measured error. The remaining error can be attributed to the representation of destination 903 in the network. The 95 Street connection to zone 903 is coded as a more direct route due to travel times westbound into the CBD being ignored.

b. 111 Avenue WBD (links 64, 54 and 44)

The error in prediction here is primarily attributed to ignoring traffic generated within the study area. The assumption that no trips

Table V.1 'Before' Comparison – Peak Hour Demand

Link	Volume Predicted veh/hr	Volume Measured veh/hr	Predicted – Measured veh/hr	% Error
14	270	360	-90	-25%
23	690	565	125	22%
24	125	320	-195	-61%
28	205	225	-20	-9%
33	250	495	-245	-49%
43	430	400	30	8%
47	375	390	-15	-4%
44	430	745	-315	-42%
53	765	770	-5	-1%
54	655	770	-115	-15%
63	730	785	-55	-7%
64	620	550	70	13%
83	30	300	-270	-90%
84	675	760	-85	-11%
93	420	490	-70	-14%
94	990	970	20	2%
104	820	800	20	2%
524	30	270	-240	-89%
506	765	900	-135	-15%
505	670	735	-65	-9%
502	30	300	-270	-90%
501	730	660	70	11%
503	1370	1300	70	5%
504	1150	1170	-20	-2%
513	140	120	20	18%

Table V.2 'Before' Comparison – Route Travel Times

Route	Predicted Travel Time (min)	Actual Travel Time (min)	Diff-erence (min)
1	6.6	7.2	0.6
2	5.4	5.8	0.4
3	5.4	6.0	0.6
4	6.5	6.5	0.0
5	5.8	5.8	0.0
6	6.1	6.4	0.3

from origin 103 have a destination to the west on 111 Avenue would also contribute to this error.

c. flows from origins 101 and 102

Examining links immediately adjacent to origins 101 and 102 indicates that excessive traffic from origin 102 is assigned to 82 Street, and origin 101 flows are over-assigned to Stadium Road. The net error is not significant, however, when flows beyond the network entry signals (115 Avenue - 82 Street and 115 Avenue - Fort Road) are considered.

The travel time comparison of Table 5.2 reveals that predicted and actual travel times are within 30 sec for each route being compared. This is not considered to be a significant error, in that 'measured' travel times used an intersection delay calculated with program SINTRAL (Ref. 38). The route travel time comparison appears to indicate that the delay algorithm used in CONTRAM produces similar results to that used in SINTRAL. This result, in turn, agrees well with field measurements at both saturated and undersaturated signals.

The issue of concern in evaluating errors is whether these errors are of sufficient magnitude to cause a poor design. The results of Tables 5.1 and 5.2 would suggest that CONTRAM predictions may be used directly for design with one adjustment; flows on 111 Avenue westbound must be increased by 300 veh/hr to reflect internal trip generation and through traffic. After this adjustment, the predicted flow pattern could be used with confidence for design purposes.

It appears then that CONTRAM is a useful and accurate model for the simulation of undersaturated network conditions.

D. After Analysis

In the analysis of 'after' conditions, a key revision was made to the network to delete Jasper Avenue, and the left lane of 112 Avenue westbound at 82 Street (links 503 and 68). Adjustments to signal timings and saturation flow were made such that the link capacities agreed with those in place on the

first day of the Kinnaird closure.

a Initial Results

Table 5.3 indicates a comparison between measured and predicted values. Some caution must be used when examining measured values, as all counts on routes other than 112 Avenue reflect conditions after the removal of the 112 Avenue barricades.

In general, predicted flows do not match well with measured values. Some of the more serious errors are:

a. Flows remaining on 82 Street are over-estimated by more than two times the actual volume.

b. Flows on 112 Avenue WBD at 82 Street were accurately predicted, but an overassignment of traffic to the Dawson Bridge existed. In total, flows from the east were over-predicted by almost 300 veh/hr or 12%.

c. Flow diversion to 115 Avenue and 95 Street was over-predicted.

Of particular interest, the sum of total flows exiting the network indicates that measured and predicted flows are equal. This balance occurs due to the flow under-estimation on 111 Avenue and 107A Avenue cancelling out a flow over-estimation on routes entering the CBD.

Explanation of Error

For flows originating in the east, it was suspected that too much flow diversion to the Dawson Bridge had been predicted by CONTRAM due to the lack of measures available to simulate a travel time 'penalty' for this longer route which involved two bridge crossings.

The over assignment of flows from the north to both 82 Street and 115 Avenue may have resulted from ignoring 'shortcutting' traffic near 112 Avenue and 86 Street. Field observations in the first days of the detour indicated substantial traffic volumes on both 113 Avenue and 114 Avenue bypassing the signal at 112 Avenue - 86 Street.

Table V.3 Initial 'After' Comparison – Peak Hour Demand

Link	Volume Predicted veh/hr	Volume Measured veh/hr	Predicted – Measured veh/hr	% Error
14	690	550	140	25%
23	575	700	-125	-18%
24	475	440	35	8%
28	355	290	65	22%
33	355	180	175	97%
34	830	740	110	15%
43	625	650	-25	-4%
47	595	450	145	32%
44	420	790	-370	-47%
53	710	780	-70	-9%
54	1205	1020	185	18%
63	365	140	225	161%
64	840	800	40	5%
83	285	390	-105	-27%
84	825	880	-55	-6%
93	645	750	-105	-14%
94	835	750	85	11%
98	610	540	70	13%
104	1150	970	180	18%
524	275	280	-5	-2%
506	730	850	-140	-14%
505	650	840	-190	-23%
502	440	400	40	10%
501	1280	1160	120	10%
504	1500	1325	175	13%
513	500	290	210	72%

b 'Shortcutting' Permitted

In light of the observations in the first 'after' analysis, several network revisions were made.

'Shortcutting' traffic through Parkdale and Norwood was permitted by the provision of link 153, connecting all flows passing through 115 Avenue – Fort Road with 111 Avenue east of 95 Street. A speed of 40 km/hr was assigned to this route.

To simulate the time penalty from a dual river crossing via the Dawson Bridge, 3 minutes was arbitrarily added to the travel time across the Capilano Bridge. This measure was expected to increase the relative travel time on this route to such an extent that some traffic would be diverted back to 112 Avenue.

Flow Predictions

Examining flows from the north, the insertion of a 'shortcutting' link resulted in a shift of 355 veh/hr from the arterial roads onto local streets. Examining the results in Table 5.4, it is apparent that the majority of the traffic has shifted from 82 Street. Overall, all links from the north show very close agreement between predicted and actual flows. In fact, almost no links experience errors outside the tolerance of 10% or 100 veh/hr.

A slight discrepancy was noted in the vicinity of 111 Avenue – 95 Street. Although total flows through this intersection are correctly predicted, an error in turning movements is indicated, due to the existence of two parallel routes south of 111 Avenue (95 Street and 96 Street).

From the east, the introduction of an additional three minutes of travel time on the Dawson Bridge route does not alter volumes during the peak hour. This suggests that congestion has reached a level where even a 3 or 4 minute delay will not affect flow assignment. In fact, both 112 Avenue and 106 Avenue are predicted to operate at capacity for the duration of the peak hour.

Travel Time Predictions

Predicted versus actual travel times in the study area are shown in Table 5.5. Predicted and actual travel times from the north indicate extremely close agreement. For these routes, moderate congestion was experienced in the 'after' case, but queue lengths did not ever exceed 25 vehicles.

From the east on 112 Avenue, the predicted route travel time of 13.7 minutes corresponded almost exactly with the 14.6 minutes experienced on Day 1 of the closure. The apparent difference in travel time between routes 4 and 6 is due to CONTRAM predicted delays at 112 Avenue – Capilano Freeway not being included in the travel time figures. With these delays included, CONTRAM predicts almost equivalent travel times for routes 4 and 6 (due to a large delay for westbound left turns onto the Capilano Freeway).

Working with fixed traffic demands from the east, no opportunity existed for traffic to find alternate routes, as both 112 Avenue and 106 Avenue were loaded to capacity. It appears, then, that working with a fixed demand, it would never be possible, using CONTRAM to lower travel times to the values experienced 2 weeks after the Kinnaird closure began. This suggests that temporal re-assignment of demand must be allowed to occur.

Permitting 'shortcutting' traffic resolved all volume discrepancies that existed for flows from the north. In the case of flows from the east, however, it appears that both queue lengths and delays have reached intolerable levels. For example, 112 Avenue WBD at 82 Street is predicted to experience peak delays of over 5 minutes, and queue lengths exceeding 100 veh/hr. These values of queue length and delay are above the values where peaking characteristics were observed to change. The Edmonton data presented in Chapter 4 indicated that peaking characteristics change when delays exceeded 4 minutes, or when queues in excess of 40 vehicles existed. In the Kinnaird area, temporal re-assignment was measured after the bridge closure, and causes an over-estimate of 200 veh/hr in CONTRAM predictions for flows from the east.

Table V.4 'Shortcutting' Permitted – Peak Hour Demand Comparison

Link	Volume Predicted veh/hr	Volume Measured veh/hr	Predicted – Measured veh/hr	% Error
14	600	550	50	9%
23	785	700	85	12%
24	475	440	35	8%
28	355	290	65	22%
33	95	180	-85	-47%
34	830	740	110	15%
43	550	650	-100	-15%
47	590	450	140	31%
44	720	790	-70	-9%
53	710	780	-70	-9%
54	935	1020	-85	-8%
63	95	140	-45	-32%
64	840	800	40	5%
83	350	390	-40	-10%
84	620	880	-260	-30%
93	780	750	30	4%
94	620	750	-130	-17%
98	580	540	40	7%
104	1200	970	230	24%
524	340	280	60	21%
506	730	850	-140	-14%
505	650	840	-190	-23%
502	320	400	-80	-20%
501	1370	1160	210	18%
504	1510	1325	185	14%
513	530	290	240	83%
153	355	(?)		

Table V.5 'After' Comparison – Route Travel Times

Route	Predicted Travel Time (min)	Actual Travel Time (min)	Difference (min)
1	7.5	7.5	0.0
2	7.0	7.0	0.0
3	n/a	n/a	
4	13.7	10.3	3.4
5	n/a	n/a	
6	6.6	6.5	0.1

The results of this simulation are of importance in evaluating CONTRAM. The model is able to deal adequately with saturated flow conditions, as demonstrated in the accuracy of flow and travel time predictions from the north. When demands result in serious over-saturation, CONTRAM is not able to effectively predict flows. In the oversaturated range, however, the queue lengths and delays predicted by CONTRAM are accurate, and provide an indication of conditions when temporal re-assignment may be expected.

c 112 Avenue Barricades Removed

To simulate conditions existing 3 weeks or more after the Kinnaird closure began, a revision was made to link 64 (112 Avenue WBD) to double the saturation flow. This compensated for the opening of a second westbound lane on 112 Avenue east of 82 Street.

Flow Predictions

The analysis with barricades removed is the only 'after' comparison where full data exists for all links in the network. The predicted results of CONTRAM are compared with measured flows in Table 5.6. The program run with the 112 Avenue barricades removed results in better agreement between measured and predicted values, particularly on 112 Avenue. Other areas showing a better match are 95 Street and Stadium Road, where the dissipation of queueing on 112 Avenue allowed flows to increase. Some errors do remain in the prediction:

a. An over-assignment of flows to Dawson Bridge remains, although 112 Avenue flows correspond almost exactly to measured values.
b. Flows using 95 Street to access the CBD are over-predicted, while 107A Avenue traffic is under-estimated. This error is due to motorists accessing the CBD to the west of 96 Street. This result was expected, as routes such as 97 Street or 101 Street would provide a more direct access to the CBD than through the use of 95 Street and east-west arteries.
c. At the 111 Avenue - 95 Street intersection, the error noted earlier in turning movement projections, remains.

Table V.6 Barricades Removed – Peak Hour Demand

Link	Volume Predicted veh/hr	Volume Measured veh/hr	Predicted – Measured veh/hr	% Error
14	615	550	65	12%
23	855	700	155	22%
24	480	440	40	9%
28	350	290	60	21%
33	75	180	-105	-58%
34	830	740	110	15%
43	570	650	-80	-12%
47	600	450	150	33%
44	775	790	-15	-2%
53	710	780	-70	-9%
54	1035	1020	15	1%
63	75	140	-65	46%
64	960	920	40	4%
83	375	390	-15	-4%
84	730	880	-150	-17%
93	800	750	50	7%
94	730	750	-20	-3%
98	600	540	60	11%
104	1120	890	230	26%
524	360	280	80	29%
506	760	850	-90	-11%
505	650	840	-190	-23%
502	420	400	20	5%
501	1410	1160	250	22%
504	1460	1235	225	18%
513	460	290	170	59%
153	355	(?)		

Peaking Predictions

In addition to flow projections, the peaking characteristics predicted by CONTRAM are of interest. Figures 5.4 through 5.7 compare CONTRAM predictions with actual peaks for 4 key intersection approaches (ie north approach of 111 Avenue - 95 Street & 112 Avenue - 86 Street, and east approach of 112 Avenue - 82 Street & 106 Avenue - 84 Street).

From the north, predicted and measured peaking characteristics exhibit good agreement. From the east, however, a poor fit exists. CONTRAM fails to predict the observed flattening of the peak at 112 Avenue - 82 Street, and over-predicts all flows on 106 Avenue. This error is again attributed to the lack of measures available in CONTRAM to flatten the peak through adjusting origin - destination data.

d Revised Demand

To estimate the impact of temporal re-assignment, the origin - destination data used by CONTRAM was altered to reflect the observed flattening of the peak along 112 Avenue. Flows from origin 103 to all destinations other than 904 (south on the Capilano Freeway) were changed to uniform demand in all time intervals between 7:00 and 8:45.

Two program runs were made; first with conditions as they existed at the start of the detour, and then with barricades removed on 112 Avenue.

Program Results

The program results for flows from the east are compared to measured values in Table 5.7. The initial trial with conditions in the first stage of the closure shows good agreement between predicted and actual flows. Although some over-assignment to Dawson Bridge remains, the error is less than 10% of total volume. The predicted travel time on 112 Avenue is 9.6 minutes, which agrees well with the 10.3 minutes measured two weeks after the closure began.

With barricades removed on 112 Avenue, an over-assignment of flows to Dawson Bridge remains (ie no shift back to 112 Avenue). An additional analysis was made using a two minute travel time penalty across

Table V.7 Peak Volumes with Adjusted Demand

Link	Initial	Analysis	Barricades	Removed
	Measured Demand	CONTRAM Results	Measured Demand	CONTRAM Results
64	800	810	920	860
54	920	900	1020	960
513	290	480	190	460
104	995	1140	890	1110
504	1325	1470	1235	1460

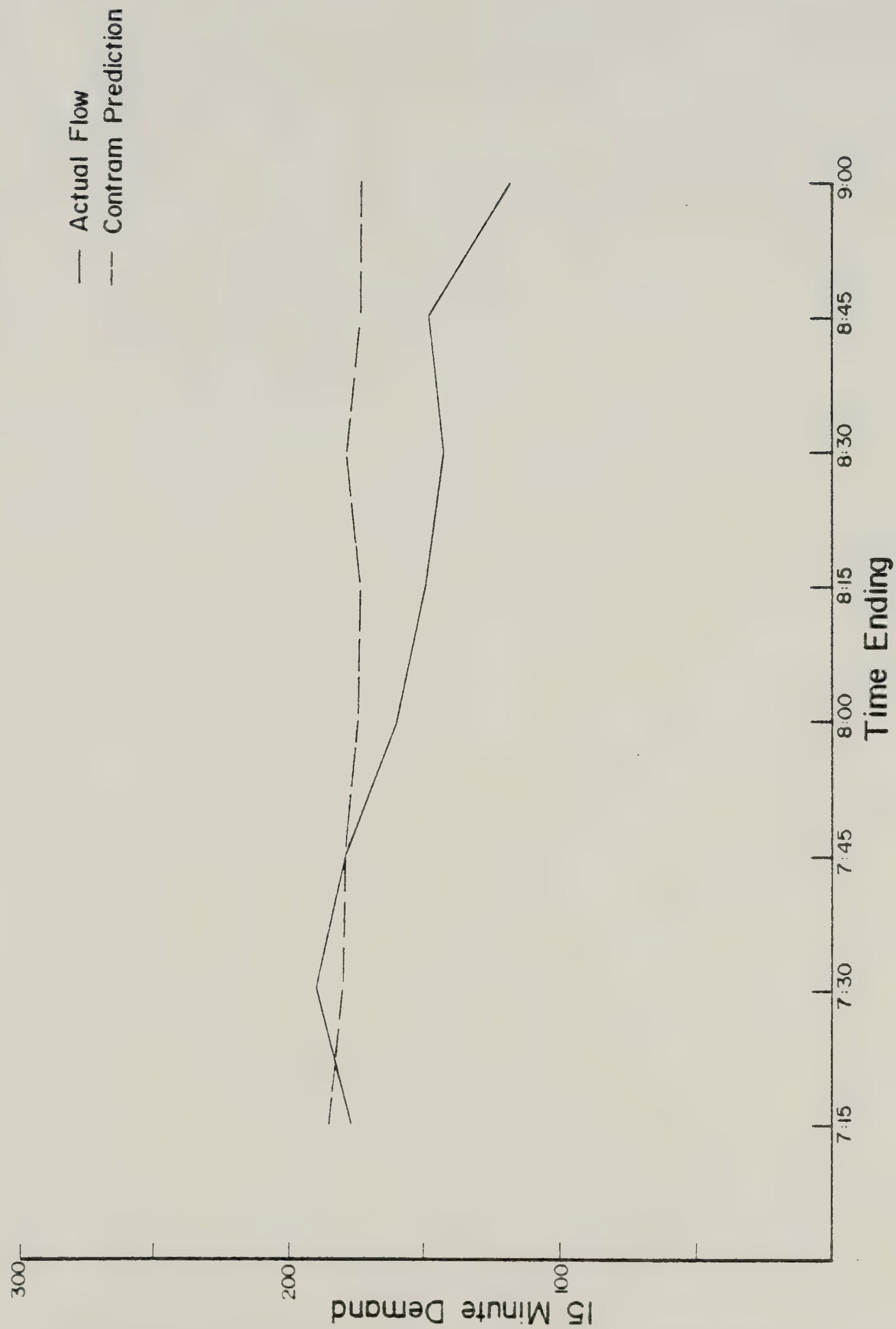


Figure V.3 Peaking Characteristics - North Approach - 112 Avenue and 86 Street

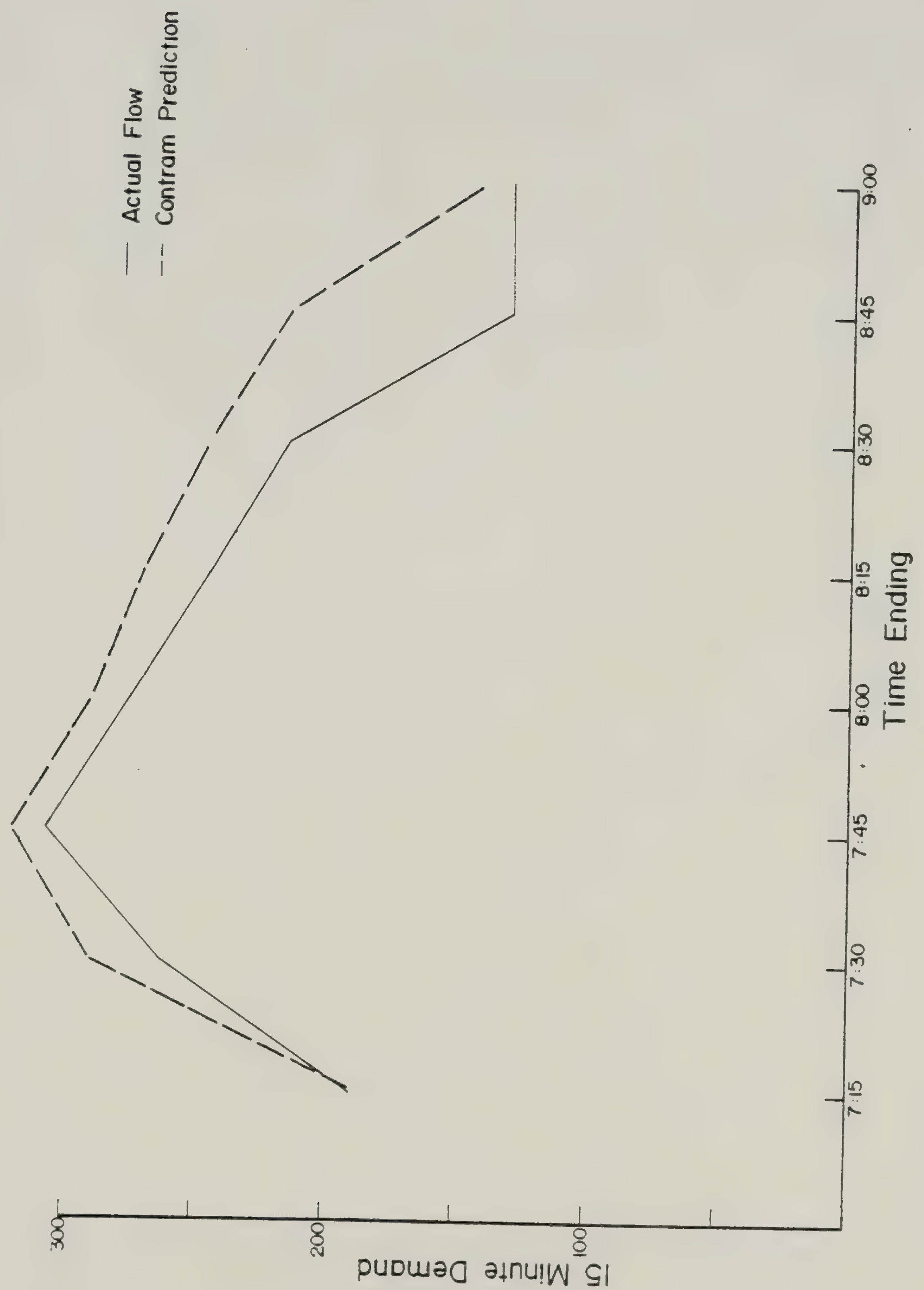


Figure V.4 Peaking Characteristics - North Approach - 111 Avenue and 95 Street

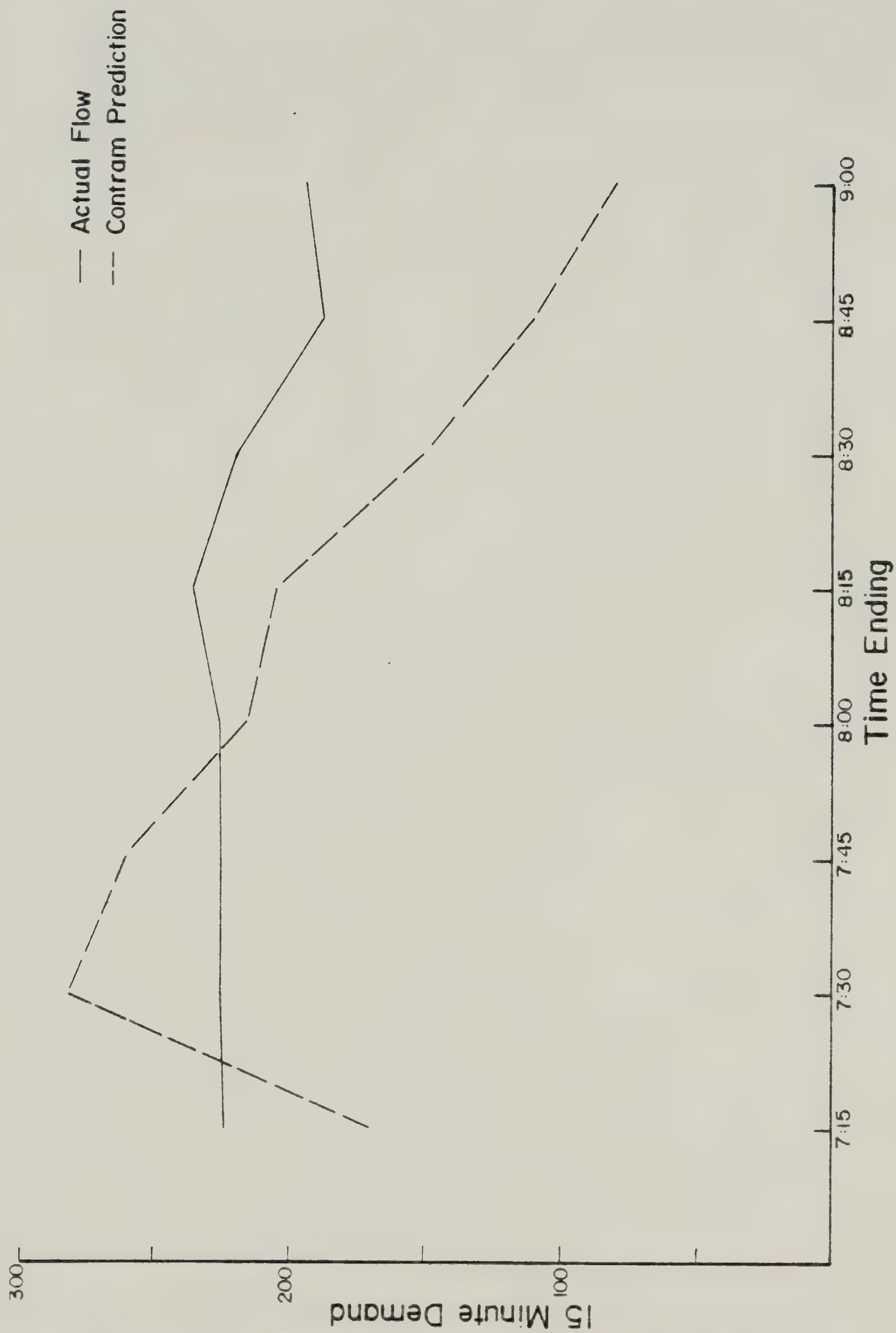


Figure V.5 Peaking Characteristics – East Approach – 112 Avenue and 82 Street

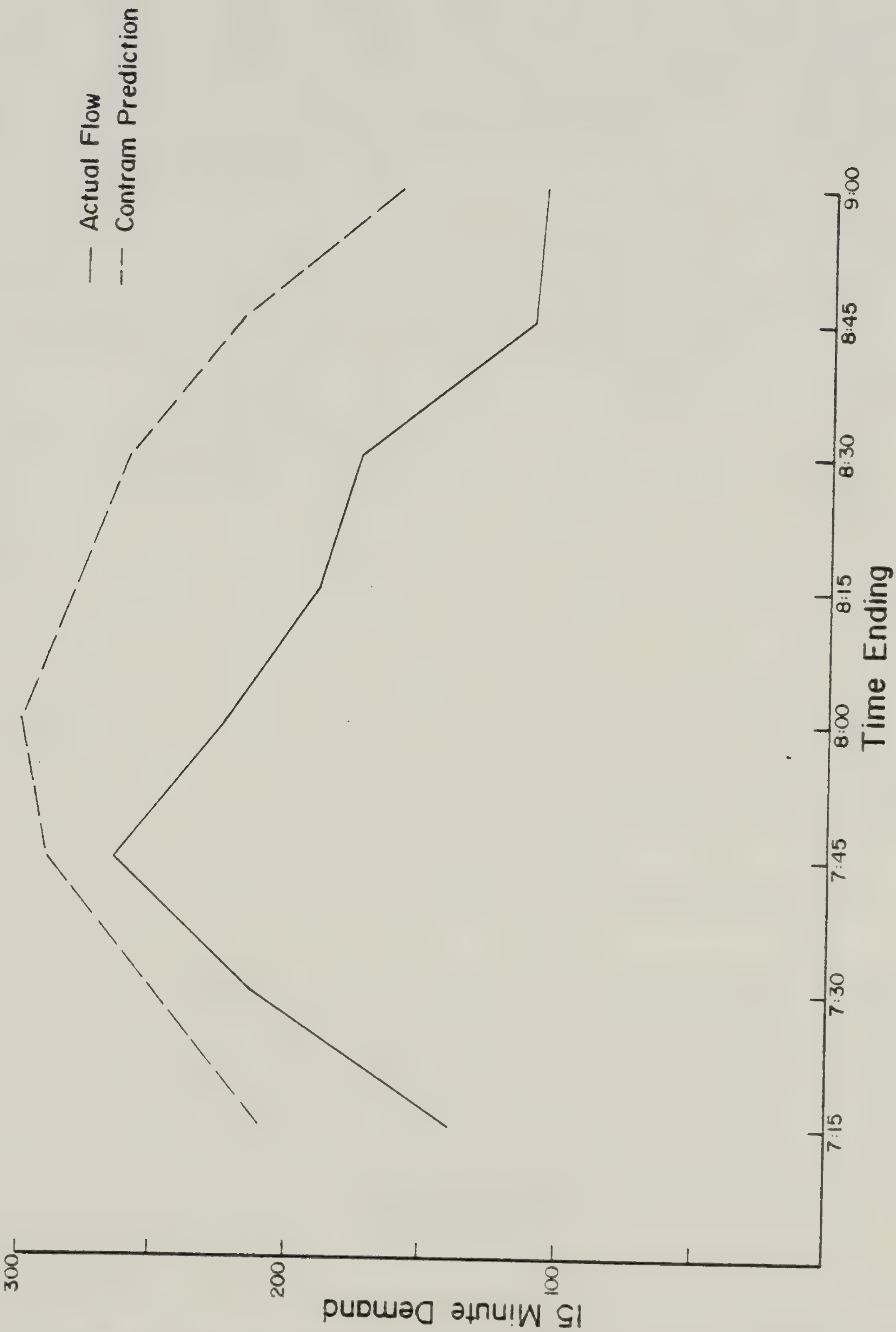


Figure V.6 Peaking Characteristics - East Approach - 106 Avenue and 84 Street

the Capilano Bridge. With this artificial increase in travel time, flows predicted reach good agreement with measured flows.

These results suggest that with under-saturated flows, people are less likely to switch to the route where two river crossings are involved. This travel time 'penalty' appears to become less important with saturated conditions, as it forms a smaller proportion of overall travel time.

e Optimized Timings

To further assess the performance of CONTRAM, an analysis was made allowing the program to optimize signal timings at three key intersections; 112 Avenue - 86 Street, 107A Avenue - 95 Street and 111 Avenue - 95 Street. Cycle times were fixed to their previous values.

Allowing timing optimization resulted in the following changes to signal phase lengths:

a. At 112 Avenue - 82 Street, east - west green time was increased to 79 sec from 51 seconds.

b. At 111 Avenue - 95 Street, green times were reduced for southbound and westbound flows and increased for southbound right turns (the phase convention defined the main phase for southbound right turns as corresponding to eastbound green).

c. At 107A Avenue - 95 Street, the westbound left turn phase was expanded.

Unfortunately, the 'optimized' timings designed by CONTRAM could not be used in practise due to the violation of minimum green times for pedestrians. At 111 Avenue - 95 Street, the 'optimized' timings were not as effective as the timings actually in use, due to the phasing convention required by the program. At this location, no fixed green time could be set for eastbound green (required due to no link being used in this direction).

Flow Predictions

Table 5.8 compares flows using optimized timings with those predicted with actual timings in use during the detour. The following key changes can be seen:

Table V.8 Optimized Timings - Peak Hour Demand

Link	Previous Predicted (Table 5.4) veh/hr	Optimized Timings Result veh/hr	Difference veh/hr
14	600	655	55
23	785	875	90
24	475	470	-5
28	355	360	5
33	95	55	-40
43	550	490	-60
47	590	710	120
44	720	760	40
53	710	715	5
54	935	1040	105
63	95	55	-40
64	840	990	150
83	350	485	135
84	620	600	-20
93	780	710	-70
94	620	595	-25
98	580	720	140
104	1200	1100	-100
524	340	475	135
506	730	760	-30
505	650	680	-30
502	320	390	70
501	1370	1440	70
504	1510	1450	-60
513	530	430	-100
153	355	330	-25

a. Volumes have shifted back from the Dawson Bridge to 112 Avenue (100 veh/hr)

b. More traffic is assigned to 96 Street, and to southbound right turns at 111 Avenue – 95 Street.

c. An increase in westbound left turns has occurred at 107A Avenue – 95 Street.

Of more importance is the reduction in travel times noted along 112 Avenue. The previous run with no adjustments to the origin – destination table predicted a travel time of 14.8 minutes, while with optimized timings this was reduced to 7.1 minutes. This result is equivalent to that obtained with the removal of the barricades on 112 Avenue.

E. The Use of CONTRAM for Design

This chapter has provided sufficient examples in the use of CONTRAM that it is possible to examine the implications that the availability of CONTRAM would have had on the design of the Kinnaird detour.

In the original design of the Kinnaird detour, it had been identified that flow diversions to 106 Avenue would occur. It was also identified that a combination of flows from 112 Avenue WBD and 82 Street SBD would overload the 112 Avenue – 86 Street signal. Flow disruption to the Northeast Light Rail Transit Line was anticipated, due to long queues extending from 112 Avenue – 86 Street. To ensure that this flow disruption did not occur 112 Avenue was reduced to a single westbound lane east of 82 Street, and restrictive timings were used at 112 Avenue – 82 Street. The resulting design met the objective of ensuring no disruption to the Light Rail Transit line, but resulted in extreme congestion on 112 Avenue. This led to both route and temporal re-assignment, as well as the generation of a high volume of public complaints.

The availability of CONTRAM for the detour design would have identified the following:

a. 'Shortcutting' traffic in Norwood could have been expected, together

with reduced volumes on 82 Street.

b. Westbound traffic on 112 Avenue need not have been as severely restricted.

The resulting savings in fuel consumption and person delay would more than justify the use of CONTRAM for design.

a Model Effectiveness

The simulations performed and discussed in this chapter allow the following major conclusions to be made about the effectiveness of CONTRAM:

a. For undersaturated conditions, flow predictions, peaking characteristics and travel times predicted agree well with measured values.

b. For moderate congestion, CONTRAM again provides accurate predictions of flows, peaking and travel times.

c. In cases involving the introduction or removal of extreme congestion as part of a network change, CONTRAM will not provide sufficient results due to the model being unable to alter the given trip table to permit temporal re-assignment.

d. Difficulties in the use of the model were encountered with travel time changes in excess of 4 minutes, or queue length changes in excess of 50 vehicles per lane.

e. The use of a travel time 'penalty' was required to prevent over-assignment on a route using two river crossings.

b Suggested Improvements

Based on the use of CONTRAM for data in the Kinnaird bridge detour, a number of suggestions for model improvements are proposed:

a. No facility currently exists for specifying minimum phase times when signal optimization is performed. This means that pedestrian clearance or minimum phase durations cannot be accounted for.

b. No facility exists to set a fixed percentage of green during signal optimization. This is required in cases when not all movements at an intersection are simulated (ie if only 3 links are simulated at a 4 phase signal).

c. A summary of degree of saturation for each link in each time interval would be of assistance when comparing alternative transportation management strategies.

c Data Limitations

The major limitation in the use of CONTRAM for analysis remains, however, in the availability of data to input into the model. Of the three types of data required, the origin – destination data is the most difficult to obtain. In the Kinnaird area, license plate surveys were used to synthesize a trip table. In most uses of CONTRAM, however, this data will not be available.

Research is currently underway (Ref. 24) to directly obtain origin–destination data from intersection counts. Until this technique is perfected, CONTRAM will require careful calibration to 'before' conditions before it may be used for prediction.

CONCLUSIONS AND RECOMMENDATIONS

The Transportation Management approach has become accepted and is widely used to provide solutions to transportation problems. T.S.M. differs from earlier approaches to transportation problem solving in that an emphasis is placed on both sides of the transportation problem; ie supply and demand, rather than concentrating on the demand side through the provision of new facilities.

Transportation Management has evolved in response to two problems faced by transportation professionals. Construction cost increases have meant that a greater emphasis is being placed on gaining the best use of existing facilities, before constructing additional facilities. Citizen involvement in planning, together with limited funding has meant that the impacts of transportation system changes must be known prior to implementation, to minimize negative impacts, and to permit the best investment per dollar expended on transportation.

In order to evaluate transportation improvements, techniques to predict impacts must be known. In addition to primary impacts (ie delay reductions), the secondary impacts after the re-establishment of equilibrium must be known. In an effort to predict the impact of T.S.M. strategies, transportation engineers have turned to computer modelling. The resulting efforts to develop models that can deal with both short term and long term impacts of T.S.M. have not fully succeeded.

In Chapter 2, existing techniques used in the evaluation of transportation demand and planning were presented. Traditional approaches tended to examine transportation issues at one of two different levels. These were either planning (traffic assignment) or operations (traffic engineering). In general, planning techniques have been directed towards the study of large networks, and the prediction of future demand for transportation and transportation corridors. As a result of this 'macro' approach, the predicted network operating characteristics may not correspond to measured values. In particular, delays at signalized intersections are not well represented, although signal delays are one of the most important influences on route selection in arterial networks. In addition, the level of detail used in planning models makes them unsuitable for evaluating

small sections of the road network, and schemes such as traffic management. At the same time, however, traffic engineering techniques can only deal with small portions of the network. Although predicted operating characteristics agree with observed values, traffic operations techniques cannot be used for prediction, unless constant demand on facilities is assumed.

A number of researchers have recognized the shortcomings of traditional techniques, and have developed new models that combine demand prediction with an accurate assessment of operating characteristics. Three of these models (TRANSIGN, CONTRAM, and Micro – Assignment) were presented in Chapter 2. The intention of each of these models is that they might be used to assess various T.S.M. strategies, and enable the selection of the most appropriate strategy, with the knowledge of impacts of the strategy. An additional feature of some of these models is the ability to simultaneously adjust arterial capacity (signal timings) while assigning traffic flows. Unfortunately, a number of limitations remain with these models. The most serious problems are:

a. testing of models with real traffic networks has been limited
b. operating characteristics other than travel times and delays are not generally dealt with
c. travel behaviour changes have been limited to an assessment of route assignment

In recognition of the need for actual measurement of travel behaviour, prior to the development of T.S.M. models, data was collected at three locations in Edmonton, in 1979. In each case, the development of a new traffic equilibrium was monitored following the implementation of a traffic management plan. Assessment of the data collected led to the following major conclusions:

a. Travel behaviour was influenced by a combination of the changes in delays and queue lengths.
b. Route re-assignment was observed when delay changes of 3 minutes per vehicle occurred.
c. Route re-assignment was observed when queue length changes of 40 vehicles per lane were observed.

d. Temporal re-asignment was observed at one location where travel time increased by 4 minutes per vehicle, queue length increased by 40 vehicles, and no alternate routes existed.

e. No mode shifts were observed in the area studied (Kinnaird Bridge).

f. Most route re-assignment was complete within one week, while temporal re-assignment required a longer time.

The importance of these findings is that only limited research efforts to date have confirmed the occurrence of temporal re-assignment. In addition, the conclusion that both queue length and delays influence travel behaviour represents a departure from considering only travel time Unfortunately, this study was not able to ascertain the relative importance of each of these factors.

The Edmonton results for the Kinnaird Detour were used as an input into the CONTRAM model to assess both the effectiveness of CONTRAM, and the importance of including temporal assignment. The availability of license plate survey data made it possible to produce an accurate trip table as an input to CONTRAM, together with measured network and control data. The use of these measured inputs led to a good match between model predictions and measured volumes and travel times in the 'before' situation. CONTRAM analysis of 'after' conditions were also effective, with the following exceptions:

a. Flows and delays on one portion of the network were overpredicted by CONTRAM. This occurred as the model does not have the ability to model temporal re-assignment, which had taken place in this area.

b. Flows were over-predicted on a route that involved two river crossings, as CONTRAM was unable to reflect the percieved additional travel time via this route. A travel time 'penalty' of two minutes had to be applied before results matched observed conditions.

a An Approach to T.S.M. Modelling

The previous chapters have provided an insight into travel behaviour and network equilibrium for three sections of the Edmonton network. The results of the Edmonton surveys, in turn, have been succesfully replicated through the use

of the CONTRAM model.

This has led to the conclusion that, using a combination of CONTRAM predictions with measured travel behaviour, it should be possible to predict, in advance, the impact of alternative Transportation Management strategies. Although not all steps in this process have been verified, it is now possible to outline a methodology to be used in the assessment of T.S.M. plans. The suggested technique would use the following approach:

1. Perform intersection counts and network capacity inventory in order to develop a network trip table and link capacities.
2. Assess existing conditions through the use of CONTRAM, and calibrate the model by comparing actual volumes to model predictions.
3. Assess alternative T.S.M. plans with the use of CONTRAM, maintaining the same origin–destination data, and allowing the optimization of signal timings.
4. Adjust travel times, where necessary if flows on some routes appear unreasonable (ie dual river crossings). and repeat CONTRAM analysis.
5. If delay changes of more than 2 minutes are predicted, review the network to determine if all feasible routes have been included (ie 'shortcut' routes).
6. Spread the demand over a broader peak by adjusting the trip table, if predicted delay changes exceed 4 minutes per vehicle at congested intersections. and then repeat CONTRAM analysis.
7. If, after all of the above analysis, delay changes in excess of 4 minutes remain, then the possibility of mode shifting should be examined.

Using this procedure, it should be possible to assess most T.S.M. options, with an adequate knowledge of network impacts. In dense networks with signal co–ordination, it may be necessary to use CONTRAM and TRANSYT simultaneously to develop optimized timings and equilibrium flows.

b Recommendations for Further Research

The results of this thesis have led to the development of a revised technique for the assessment of T.S.M. strategies. With the ability to accurately forecast impacts, the transportation engineer is in a much better position to

recommend the course of action to be taken to resolve transportation problems or prevent negative impacts.

It has also been identified, in the course of this research, that a number of important impacts of T.S.M. plans have not been fully researched or measured. It is recommended, therefore, that research continue in order to confirm that the T.S.M. planning approach outlined in the previous section agrees with observed data. Research needs identified from this thesis include:

1. Additional studies of temporal assignment must be performed at a number of locations. The objective of this research would be to quantify the magnitude of temporal re-assignment for different levels of congestion.
2. The relative importance of queue lengths versus delays in altering travel behaviour must be determined.
3. Determine under what conditions that a network change can induce mode shifting, in both the short term and long term.
4. The effects of signal co-ordination on route selection must be determined.
5. The CONTRAM delay and capacity relations for priority ruled intersections must be validated for Alberta conditions.
6. The influence of road class on route selection should be investigated (ie 'shortcut' routes, arterial standard) to develop a set of travel time or capacity 'penalties'.
7. Additional testing and validation of CONTRAM is required.

BIBLIOGRAPHY

a References

1. Akcelik,R., "A Mathematical Analysis of Route Control", *Proc. 7th International Symposium on Transportation and Traffic Theory* , Kyoto, 1977, pgs 413-432

2. Akcelik, R., "A New Look at Davidson's Travel Time Function", *Traffic Engineering and Control*, Vol. 19, October, 1978, pgs 459-463

3. Akcelik, R. and Maher, R., "The Re-distributional effects of an Area Traffic Control Policy" ,*Traffic Engineering and Control*, Vol. 18, 1977, pgs 383-385

4. Alfa, A.S. and Minh, D.L., "A Stochastic Model for the Temporal Distribution of Traffic Demand - The Peak Hour Problem" ,*Transportation Science*, Vol. 13, November, 1979, pgs 315-324

5. Allsop, R.E., "Delay at a Fixed Time Traffic Signal, I - Theoretical Analysis", *Transportation Science*, Vol. 6, 1972, pgs 260-285

6. Allsop, R.E., "Use of Traffic Signals to Influence the Amount and Routeing of Traffic", University of Newcastle Upon Tyne, Transportation Operations Group, Paper #13

7. Allsop, R.E. and Charlesworth, J.A., "Traffic in a Signal Controlled Road Network : An Example of Different Signal Timings Inducing Different Routings", *Traffic Engineering and Control*, Vol. 18, May, 1977, pgs 262-266

8. Branston, D., "Link Capacity Functions - A Review", *Transportation Research*, Vol. 10, 1976, pgs 223-236

9. Brown, A., *An Analysis of the Traffic Signal Network in the Eastern Portion of the Edmonton Downtown Area*, University of Alberta, Department of Civil Engineering, M. Eng. project, 1977

10. Brown, G.J. and Scott, R., "Micro - Assignment: A New Tool for Small Area Planning", *Highway Research Record #322*, Highway Research Board, Washington, 1970, pgs 149-161

11. Catling, I., "A Time Dependent Approach to Junction Delays", *Traffic Engineering and Control*, Vol. 19, November 1977, pgs 520-523

12. Charlesworth, J. A., "The Calculation of Mutually Consistent Signal Settings and Traffic Assignment for a Signal Controlled Road Network", *Proc. 7th International Symposium on Transportation and Traffic Theory*, Kyoto,

1977, pgs 545-561

13. Charlesworth, J.A., "Control and Routeing of Traffic in a Road Network", *Traffic Engineering and Control*, Vol. 20, October 1979, pgs 460-466

14. Charlesworth, J.A., "Equilibrium Assignment of Traffic to Road Networks Containing Signals - The Need for Multi-valued Link Travel Times", *Traffic Engineering and Control*, Vol. 21, March 1980, pgs 108-109

15. Chumak, A.,Braaksma, J.P.,"Implications of Travel Time Budget for Urban Transportation Modelling in Canada", presented at the 60th Annual Me the Transportation Research Board, Washington, January, 1981

16. City of Edmonton, Traffic Operations, *Project Uni Final Report*, 1979

17. City of Edmonton, Traffic Operations, *Project Uni Working Paper #6 -Traffic Impact*, 1979

18. City of Edmonton, Traffic Operations and The University of Alberta, Transportation Engineering Group, *Saturation Flow Manual*, April, 1980

19. City of Edmonton, Transportation Planning, *Overview of the Prediction of Travel Demand: Transportation Models*, 1977

20. Dawson, J., "Comprehensive Traffic Management in York: the Monitoring and Modelling", *Traffic Engineering and Control*, Vol. 20 November 1979, pgs 510-515

21. Dial, R., "A Probabilistic Multipath Traffic Assignment Model which Obviates Path Enumeration", *Transportation Research*, Vol. 5, 1971, pgs 83-111

22. Florian, M. and Nguyen, S., "An Application and Validation of Equilibrium Trip Assignment Methods", *Transportation Science*, Vol. 10, November, 1976, pgs 374-390

23. Gerlough, P.L. and Huber, M.J., *Traffic Flow Theory*, Transportation Research Board, Special Report #165, Washington, 1975

24. Hauer, E. and Shin, B-Y.T., "Origin - Destination Matrices from Traffic Counts: Application and Validation on Simple Systems", *Traffic Engineering and Control*, March, 1981, pgs 118-121

25. Horn, B.E., "Keeping Pace with Urban Transportation Developments: An International Review of Systems Management Research", *ITE Journal*, Vol. 51, #1, January, 1981, pgs 30-39

26. Hunt, D., *Program Descriptions - License Plate Sorting Programs*, The University of Alberta, Civil Engineering, August, 1981

27. Hutchinson, T.P., "Delay at a Fixed Time Traffic Signal II – Numerical Comparison of Some Theoretical Expressions", *Transportation Science*, Vol. 6, 1972, pgs 286–305

28. Jovanis, P. and May, A.D., "Alternative Objectives in Arterial Traffic Management", submitted to 57th Annual Meeting of the Transportation Research Board, Washington, 1978

29. Leonard, D.R., Tough, J.B., Baguley, P.C., "CONTRAM: A Traffic Assignment Model for Prediction of Flows and Queues During Peak Periods", *T.R.R.L. Report LR 841*, Department of the Environment, Crowthorne, England, 1978

30. Levin, M. and Brewer, K., "Estimation of Traffic Equilibrium", *Traffic Engineering*, August 1971, pgs 38–41

31. Lucas, C. and Davidson, K.B., *Quantitative Evaluation of Traffic Assignment Methods*, Bulletin #17, University of Queensland, Department of Civil Engineering, May 1974

32. Manheim, M.L., "Toward More Programmatic Planning", in Gray, G.E. and Hoel, L.A., *Public Transportation: Planning, Operations and Management*, Prentice Hall, Englewood Cliffs, New Jersey, 1979

33. May, A.D., "Demand–Supply Modelling for Transportation System Management", presented at the 60th Annual Meeting of the Transportation Research Board, Washington, January, 1981

34. May, A.D., Clausen, T.J., Kruger, A.J., "Development and Application of Traffic Management Models – An Executive Summary", *Proc. 7th International Symposium on Transportation and Traffic Theory*, Kyoto, 1977, pgs 413–432

35. Robertson, D.I., "TRANSYT Method for Area Traffic Control", *Traffic Engineering and Control*, Vol. 11, October 1969, pgs 276–281

36. Robertson, D.I., "Traffic Models and Optimum Strategies of Control – A Review", *Proc. of the International Syposium on Traffic control Systems*, Berkeley, 1979, Vol. 1, pgs 262–288

37. Sagi, G.S. and Campbell, L.R., "Vehicle Delay at Signalized Intersections – Theory and Practice", *Traffic Engineering*, February 1969, pgs 32–40

38. Stephenson, B., Schnablegger, J., Teply, S., "Edmonton Version of Critical Lane Analysis: SINTRAL, An Interactive Computer Program System", *ITE Journal*, August, 1981

39. Stephenson, B., Teply, S., "Network Aspects of Traffic Signals and Network Travel Behaviour", paper prepared for the CORS/TIMS/ORSA Annual Meeting, Toronto, May, 1981

40. Tough, J.B., "Userguide to CONTRAM, Draft Issue", Transport and Road Research Laboratory Note, Crowthorne, England, August, 1979

41. Wardrop, J.G., "Some Theoretical Aspects of Road Traffic Research", *Proc. of the Institute of Civil Engineers*, 1952, Part II, pgs 325-378

42. Webster, F.V., "Traffic Signal Settings", *Road Research Technical Paper #39*, Her Majesty's Stationery Office, London, 1958

43. Webster, F.V. and Cobbe, B.M., "Traffic Signals", *Road Research Technical Paper #56*, Her Majesty's Stationery Office, London, 1966

44. Yagar, S., "Potential Demand Response to Improved Roadway Service", *Traffic Quarterly*, Vol. 27, January 1973, pgs 133-143

45. Yagar, S., "A Study of the Travel Patterns in a Corridor with Reference to the Assignment Principles of Wardrop", *6th International Symposium on the Theory of Traffic Control*, pgs 165- 181

46. Yagar, S., "CORQ - A Model for Predicting Flows and Queues in a Road Corridor", *Transportation Research Record #530*, Transportation Research Board, Washington, 1975

b Resource Documents

Working Paper #1, Thesis Proposal, February, 1979

Working Paper #2, Study Objectives and Procedures, July, 1979

Working Paper #3, Kinnaird Closure Surveys, July, 1979

Working Paper #4, Fort Road - 66 Street; A) Survey Procedures, B) Flow and Delay Analysis, November, 1979

DFIX Program Description, July, 1979

DACT Program Description, January, 1980

Discussion Paper #1, Kinnaird Bridge Closure - Traffic Impact, May, 1979

Discussion Paper #2, Kinnaird Bridge Closure, July, 1979

Discussion Paper, Fort Road - 66 Street, March, 1980

Discussion Paper, West End T.M.S. Plan - Phase 1, February, 1980